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Fraunhofer Institute for Telecommunications

Heinrich-Hertz-Institut, HHI
Annual Report

Annual Report

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Contents

Prof. Martin Schell (l.) and
Prof. Thomas Wiegand (r.)

Preface

Digitalization is a comprehensive approach to developing solutions that provide effective ways of rising to the challenges faced by society. Digital processes that work well are essential for creating a good quality of life – in a world where food production is sustainable, healthcare coverage is universal and personal data are secure. Promoting digitalization is one of our guiding principles here at Fraunhofer HHI, and it is reflected in every area of our research. The diverse array of subject areas we deal with puts us in a position to help society achieve progress in numerous areas.

Video conferencing was used extensively during the COVID pandemic – and the video compression research taking place at Fraunhofer HHI made significant contributions to this technology. Today, more than 50% of all the bits on the internet are formatted using video codecs we have had a hand in developing.

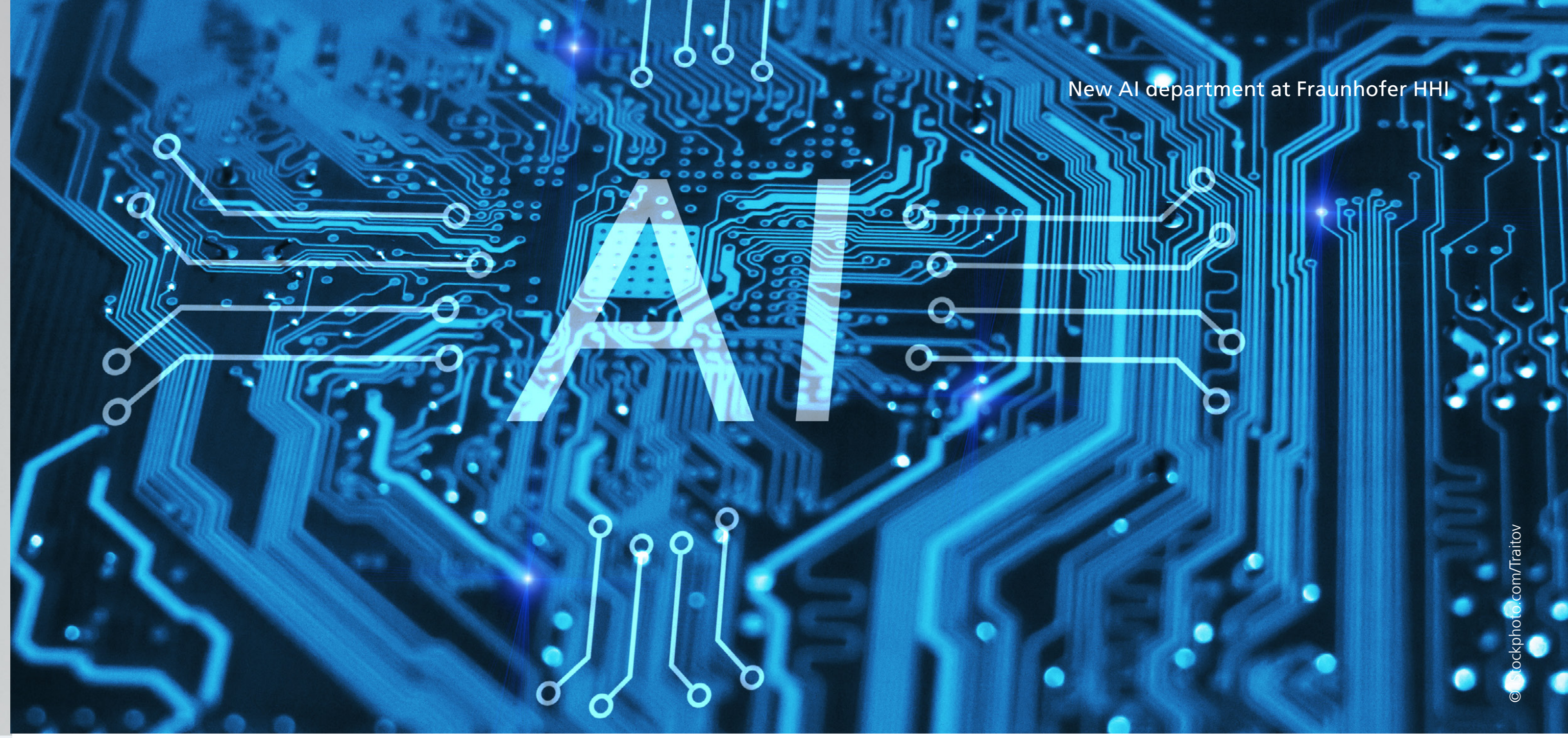
We have seen an increase in the number of cyber attacks in recent years, which is why it is vital that we keep developing quantum cryptography, a technology that secures communication by exchanging quantum keys. As part of the QuNET initiative, we work with partners on driving forward quantum communications.

Through our work in AI explainability, we are doing our part to make it possible to use AI reliably in security-critical areas in the near future. This AI-related work is also brought to a worldwide audience by means of international standardization and through ITU focus groups involving the WHO, WMO, UNEP and FAO.

Our experts in wireless communications have begun the task of developing the next-generation wireless standard, 6G. To achieve this, they have managed to obtain funding for their 6G-RIC project from the German Federal Ministry of Education and Research (BMBF) – the largest project to receive BMBF funding. 6G will make it possible to provide universal opportunities for using digital twins and augmented reality - two areas that our experts are developing for computer vision purposes.

Our researchers working in the area of sensors have achieved advancements in performance and developed new industrial applications. This is enabling them to work in a way that conserves resources and use the fiber-optic infrastructure for more applications.

In our annual report, we showcase our research departments, our highlights and everything else that has marked an important step for us.



Shaping the future
New AI department at Fraunhofer HHI

Fraunhofer HHI is one of Germany's leaders in artificial intelligence (AI) research. With the aim of reinforcing this position, in 2021 the institute established a new research department dedicated to this important subject. Since then, Prof. Wojciech Samek and his team have been working hard on advancing their multiple award-winning basic research into AI and developing it with a focus on industrial applications.

The new department arose out of the Machine Learning research group in the Video Communication and Applications department, immediately kicking things off with an experienced team that was able to expand on the focus of the group using a solid foundation of research work. The Explainable Artificial Intelligence, Applied Machine Learning and Efficient Deep Learning research groups develop solutions for the challenges that AI is currently facing, namely explainability, energy efficiency and expanding its fields of application.

Through the new department, Fraunhofer HHI is advancing its expertise in Berlin as a location for AI research and within the global AI community. The researchers are already working on several international projects, looking at the development of AI systems in skin cancer detection, air quality improvement, medical assistance systems, heat protection in urban areas, early-warning systems and digital rail operations.

Our aim is to completely rethink AI by moving away from a centrally trained, opaque form of AI that gobbles up data and energy, and instead toward something that is always learning and has green attributes – something that is able to explain its decisions and is conscious of its own inherent uncertainties.“

Prof. Wojciech Samek
Head of the Artificial Intelligence Department

76
institutes

- Main locations
- Secondary locations

The Fraunhofer-Gesellschaft (FhG)

With approximately 30,000 employees and 76 institutes, Germany's Fraunhofer-Gesellschaft is the world's foremost applied research organization.

More than 90 years of innovation for the digital society

Through its achievements in digital infrastructure research, Fraunhofer HHI has played a major role in shaping and advancing digitalization.

The Fraunhofer Heinrich-Hertz-Institut

Located in Berlin, the research institute was founded in 1928 as the Heinrich-Hertz-Institut für Schwingungsforschung (HHI for research on oscillations) and has been part of the Fraunhofer-Gesellschaft since 2003. Through its achievements in digital infrastructure research, Fraunhofer HHI has played a major role in shaping and advancing digitalization.

The demands being placed on broadband capacity are rising all the time, but progress in expanding digital infrastructure is lagging behind even in industrialized nations, making it difficult to rise to this challenge. As part of its research, Fraunhofer HHI is working to ensure that digital infrastructure is constantly improving on its performance.

Over the years, many of the innovations developed by Fraunhofer HHI researchers have gained worldwide recognition and visibility – and today, almost every second bit on the internet is shaped by Fraunhofer HHI technology in two ways:

- During data transmission, around 50% of bits on the internet are formatted using the video coding technology which Fraunhofer HHI played a major role in developing.
- There is a 50% likelihood that a bit being transmitted over the internet will encounter a photonic component whose core has been developed at Fraunhofer HHI. In many cases, these will even have been constructed in the in the institute's cleanroom.

Fraunhofer HHI building, Berlin

Around 570 employees deal with an extensive range of digitalization-related subjects across seven research departments. Working in three different locations, they focus on optical networks and systems, photonic components, fiber optical sensor systems, wireless communications and networks, video communication and applications, vision and imaging technologies, and artificial intelligence.

Over
50%
of bits on the internet are based on the work undertaken at Fraunhofer HHI

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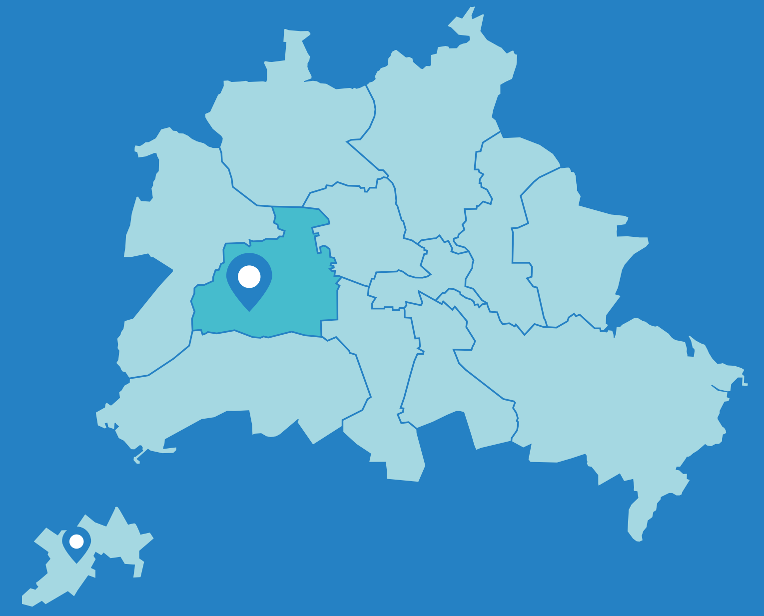
Fraunhofer HHI facts and figures

Locations

Berlin
Goslar



Staff*

	Permanent staff	Students
2017	331	206
2018	339	236
2019	375	240
2020	361	304
2021	386	281

* headcount

Chairs

University	Department	Since
Technische Universität Berlin	Optic and Optoelectronic Integration Prof. Dr. rer nat. Martin Schell	2012
	Media Technology Prof. Dr.-Ing. Thomas Wiegand	2008
	Photonic Communication Systems Prof. Dr. -Ing. Ronald Freund	2017
	Network Information Theory Prof. Dr.-Ing. habil Slawomir Stanczak	2015
	Terahertz Sensor Technology (as part of the EDCF) Prof. Dr. rer. nat. Björn Globisch	2019
	Advanced Wireless Communications Prof. Dr. rer. nat. habil. Volker Jungnickel	2021 Previously AP
	Associate Professor PD Dr.-Ing. Oliver Schreer	2006
Humboldt Universität Berlin	Visual Computing Prof. Dr.-Ing. Peter Eisert	2009
Freie Universität Berlin	Image Signal Processing Prof. Dr.-Ing. Heiko Schwarz	2017
University of Potsdam	Embedded Systems Architectures for Signal Processing Prof. Dr.-Ing. Benno Stabernack	2008
Clausthal University of Technology	Applied Photonics Prof. Dr. rer nat. Wolfgang Schade	1998
	Extraordinary Professor Ext. Prof. Dr. Eike Hübner	2016

Scientific excellence

	Master's/graduate	Doctorates	Publications	Patents
2017	33	27	537	50
2018	28	21	514	53
2019	31	24	526	67
2020	39	21	625	67
2021	45	21	651	66

3rd place*

* FhG's field-specific citation rate

Total budget in euros (million)

	2017	2018	2019	2020	2021
Total	53,5	56,9	62,4	63,9	71,3
Industry contracts	24,2	22,9	25,4	25,8	23,9
National projects	9,6	11,1	13,5	14,0	18,6
EU projects/Other	7,3	7,7	9,4	11,0	8,7
Base funding	12,4	15,2	14,1	13,1	20,1

Investments

2017	2018	2019	2020	2021
5,8	4,3	5,2	4,0	8,9

Members of the board of trustees

Senior representatives from science and industry lend their support to Fraunhofer HHI's work.

Honors from recent years

Between 2019 and 2021, researchers at Fraunhofer HHI received a range of honors recognizing their research work in various areas:

2019

1.

Leopoldina

Leopoldina, the German National Academy of Sciences, appointed Prof. Thomas Wiegand as a member of its Informatics section.

2.

Photonic Integrated Circuit Lifetime Achievement Award

At the PIC Awards, held at the PIC International Conference, Prof. Martin Schell was the recipient of the Lifetime Achievement Award in recognition of his life's work in the area of PIC development.

3.

Klung-Wilhelmy-Wissenschafts-Preis

The Faculty of Electrical Engineering and Computer Science at TU Berlin honored former Fraunhofer HHI researcher Dr. Christian Schmidt with this dissertation award given by the Dr. Wilhelmy Foundation. He received the prize as a commendation for the dissertation he completed at Fraunhofer HHI.

2020

4.

Förderpreis-ARD/ZDF

Former Fraunhofer HHI researcher Dr. Jennifer Rasch received the ARD/ZDF Women + Media Technology Award. The dissertation that she completed at Fraunhofer HHI was selected as one of the three best degree papers of the year.

5.

Hugo-Geiger-Preis

Dr. Sebastian Lapuschkin, head of the Explainable Artificial Intelligence research group at Fraunhofer HHI, was honored with the prestigious Hugo Geiger Prize. He received this in recognition of his doctoral thesis, as part of which he developed the XAI process known as layer-wise relevance propagation.

6.

Best Trainee

Business administration trainee Charlyn Domke was honored by the Fraunhofer-Gesellschaft as one of the best trainees of the year. She passed her training at Fraunhofer HHI with the grade "Excellent" and was joined in the award by Martina Keil, whose outstanding service was also recognized.

2021

7.

Applied Photonics Award

TU Clausthal student Luise Hoffmann received the Applied Photonics Award for young talent following the completion of an outstanding master's thesis with the support of Fraunhofer HHI.

8.

Best Open Source Project Awards der ICME

The Fraunhofer Versatile Video Encoder (VVenC) developed at Fraunhofer HHI scooped first place at the Best Open Source Project Awards held at the IEEE International Conference on Multimedia and Expo (ICME).

Top left: Prof. Martin Schell at the PIC Awards; middle: Dr. Sebastian Lapuschkin receiving the Hugo Geiger Prize; right: Dr. Christian Schmidt receiving the dissertation award from the Dr. Wilhelmy Foundation

Fraunhofer HHI Focus Topics

Pioneering technologies and solutions

The highlights of Fraunhofer HHI's research over the last three years reflect its future strategic orientation. The institute is a byword for applied research across a broad spectrum of communication technologies. There is a constantly growing need for interdisciplinarity, particularly as researchers become involved in increasingly interdepartmental projects, covering topics such as artificial intelligence, quantum communication, LiFi, augmented reality, mixed reality and image analysis for Industry 4.0, all the way through to medical applications.

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> **We might consider the perceptron as a black box."**
>
> **Frank Rosenblatt, 1957**
> The perceptron – A perceiving and recognizing automaton

From explainable AI to trustworthy AI

AI offers huge potential benefits in a variety of application areas, where it is not just the performance of the AI system as measured in the lab that is the decisive factor, but also the transparency of its predictions. In response to this requirement, Fraunhofer HHI has established research into explainable artificial intelligence (XAI) as one of its main topics. The institute's Layer-wise Relevance Propagation (LRP) method, developed in partnership with the Technical University of Berlin (TU Berlin), allows users to understand the decision-making basis of individual AI predictions and is one of the mostly widely used XAI technologies all over the world.

Explainable AI beyond transparency

Over the last four years, Fraunhofer HHI has been working to systematically enhance the LRP process and to optimize and successfully deploy it for various AI problems beyond classification (e.g. clustering, anomaly detection, regression) and for areas of application such as medicine (e.g. gait analysis, histopathology, dermatology, neuroimaging and epidemiology). Further XAI tools have been developed that build on LRP. These include Spectral Relevance Analysis (SpRAy) and the Class Artifact Compensation Framework (ClArC). SpRAy enables users to lift the lid on systematic behavior patterns and prediction strategies in AI models beyond individual decisions, and to explain them. Meanwhile, ClArC enables precise and efficient corrections to be made to undesired behavior patterns that have been learned within the AI models. These new XAI tools provide a way of systematically debugging AI models and therefore pave the way for a transition from explainable to trustworthy AI.

Other areas of application for the XAI methods developed at Fraunhofer HHI go far beyond the goal of increasing transparency. For instance, LRP can be used to conduct functionality evaluations of the internal structures of AI models, allowing non-functional elements to be compressed or removed. This yields enormous efficiency gains in terms of model size, prediction times and energy requirements. Applying the principle of "keep the best and remove the rest" allows very large models to be distilled down to a hundredth of their original size, without any drop in performance.

Fraunhofer HHI is currently eagerly working on new approaches to explainability (XAI 2.0), which can be used to explain AI predictions in a way that humans can understand. These explanations are provided in the form of generally understandable visualizations, which can also be used as an interface for interacting with the AI model in a variety of ways (e.g. correcting the model by correcting the explanation).

Auditing and certification of AI systems

In critical areas of application such as mobility, biometrics and medicine, transparency is not the only essential characteristic of AI systems. They also need to be secure, robust and reliable. To ensure that AI-based systems meet these requirements, an AI auditing process and specific AI certification procedures need to be developed. To this end, Fraunhofer HHI, the German Technical Inspection Association (TÜV) and the German Federal Office for Information Security (BSI) organized two "Auditing AI Systems" workshops, which took place in October 2020 and October 2021. These were attended by international AI specialists at the Berlin CINIQ Center/Forum Digital Technologies to lay out the groundwork for an auditable AI system. The participants published the outcomes of their discussions in two whitepapers*.

Fraunhofer HHI is working intensively to put its expertise in explainable AI, model debugging and verification/validation of modern AI systems towards developing future AI standards that will ensure the responsible use of the technology in health and other safety-critical areas, such as autonomous driving. These standards need to include both qualitative and quantitative quality control procedures along the entire AI life cycle in order to ensure that the AI tools are precise, robust, fair and trustworthy as a whole.

AI standards for health and medicine: ITU/WHO Focus Group on AI for Health

The applications in clinical and public health that could benefit from AI-supported automation are many and varied. Before and whilst using any AI tool in practice, it is vital to ensure that the method and its implementation are safe and effective and that they can be trusted to perform the function for which they are deployed. Here it is also important to ensure that the AI tools – developed and tested under laboratory conditions – do actually work in clinical working environments. Ideally, these tools should be equally deployable in different environments, clinics and German states.

In 2018, the International Telecommunication Union (ITU) and the World Health Organization (WHO) created a focus group on the topic of "AI for Health" (FG-AI4H) as a shared initiative for exploring standardization options in this area. The FG-AI4H is led by Prof. Thomas Wiegand, Executive Director of Fraunhofer HHI, and receives expert and organizational support from the AI department. The FG-AI4H establishes processes and the associated guidelines and issues reference documents containing best practices. This also includes annotation tools and an AI test platform.

* To the whitepapers

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Virtual humans – modelling, interaction and streaming

Building on the acclaimed volumetric video technology developed by Fraunhofer HHI researchers, methods for modelling interactive virtual people have been developed, along with streaming technology for latency-free transmission. The purpose of these technologies is to make meeting and interacting with virtual people a reality. The new methods are opening the door to interacting with realistic virtual people in virtual reality (VR) and augmented reality (AR) environments.

Volumetric video

The technology used to generate volumetric video records real people with multiple cameras at the same time. This allows highly realistic dynamic 3D models to be created, which can then be viewed from multiple angles in a virtual scene. Fraunhofer HHI has its own recording system consisting of 16 stereo cameras and approx. 150 light panels that can capture 3D information about the person from all directions. Using the same principle as the human eye does to achieve three-dimensional vision, this technology allows 3D geometry to be captured, fused and transposed into a consistent, naturalistic and dynamic 3D representation of the person. It has established itself as an important step in the development of media production around the world. Content produced by Fraunhofer HHI has been presented in many VR productions. This includes enabling visitors to the Sachsenhausen concentration camp memorial to have a three-dimensional life-sized virtual encounter with Holocaust survivor Ernst Grube using virtual reality glasses.

From volumetric video to virtual people

Volumetric video allows highly realistic dynamic models of previously recorded actions to be reproduced and passively observed. Now, building on these highly realistic data, Fraunhofer HHI researchers have developed methods for generating interactive virtual people. This involves using hybrid models that combine semantic information from animatable computer graphic models with highly realistic volumetric video data and the latest methods in AI-based animation and neural rendering. The first step in this process is adapting the geometry of the computer model to the volumetric scan. Next, the concordance between the two formats is calculated so that the animations and semantic information from the computer graphics model can be transferred to the volumetric scan. This allows a virtual person to maintain eye contact with the user, for example. This technology has been successfully introduced into the new MPEG standard.

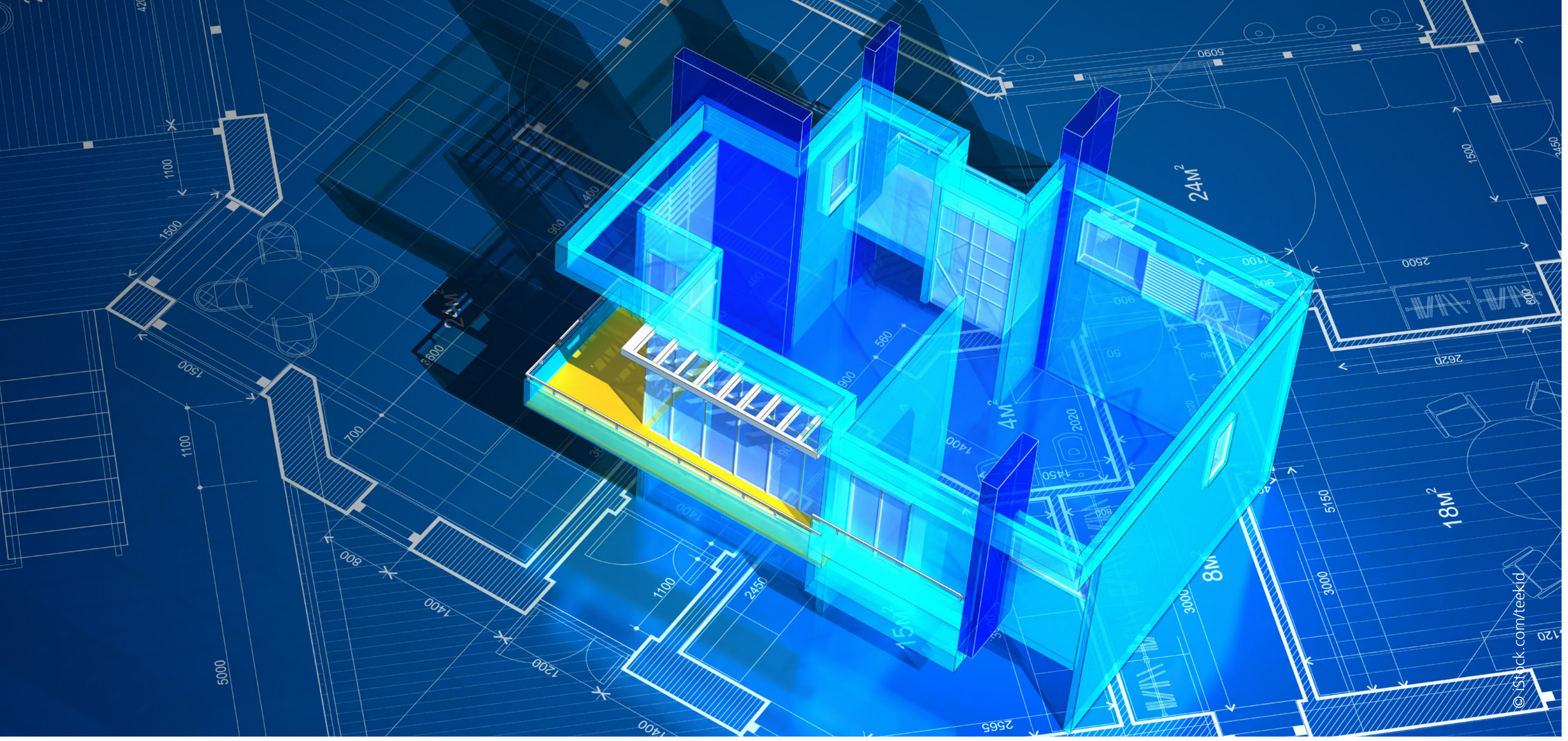
It also makes synthesizing entirely new movements possible. Using the latest AI methods, unique personal movement patterns or facial expressions are learned from the enriched volumetric video data, which then allows generative models to synthesize new movements or facial animations, and to do so in a way specific to the individual person. Methods for generating personalized animatable facial models for use in visual speech synthesis have been developed in this way, amongst other uses. These can realistically synthesize animation that matches spoken text or speech. Gestures and movements can also be learned and synthesized based on the language. This can then be used, for example, to provide immersive video-conferencing systems in virtual rooms. There is also scope for enormous advances in online teaching as a result. Students can interact with highly realistic avatars of lecturers using a mixed reality (MR) headset, allowing the interactivity of in-person teaching to be combined with the flexibility and inclusion of online teaching.

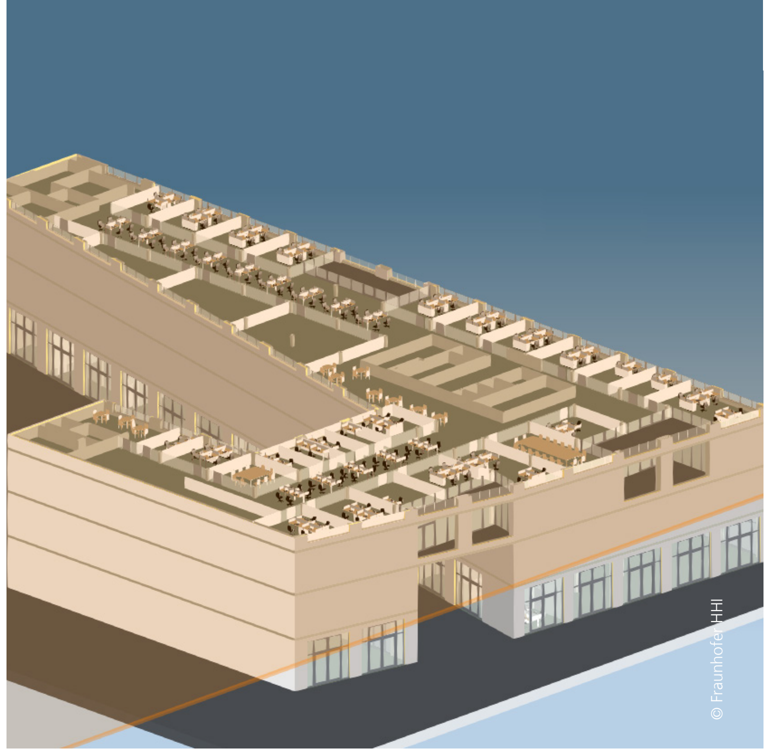
In addition to the technological developments, the ethical and perception theory considerations are also vital in this context. These are being investigated in close cooperation with ethicists and neuroscientists.

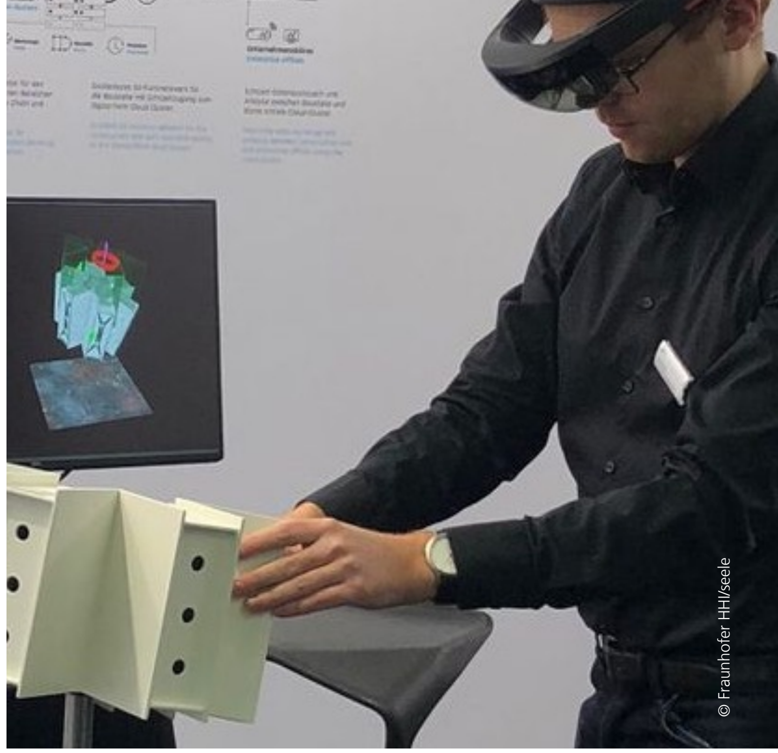
Streaming and transmission

To facilitate efficient transmission and display of interactive volumetric videos on mobile devices, Fraunhofer HHI researchers have developed a transmission process that outsources the energy-intensive rendering process to an edge cloud. The rendered video is transmitted as normal 2D video, decoded and integrated into the scene on the glasses. In the other direction, the glasses transmit line-of-sight information to the edge cloud in order to position the render camera on the server in sync with the user's movements, and to turn the avatar's head towards the correct direction, for example. This process has to be rapid, of course.

A situation where the professor is always looking at where the student was a moment ago, i.e. always looking slightly away from them, could hardly be described as realistic. The latency required is under 40 milliseconds in both directions. The system that has been developed achieves this latency by optimizing all of the components of the WebRTC standard recognized in online conferencing, a machine learning-based estimation of the future movement of the user and an extremely rapid system for adjusting the data rate to the bandwidth available in the radio channel via direct feedback from the network.







Left: generating BIM models from 2D plans. middle: BIM model as digital twin of a building. right: AR assistance supporting complex assembly tasks.

Digital twins and AI in construction engineering

The construction industry currently has major challenges to overcome in order to keep up with the major demand for new construction, upkeep, energy-saving refurbishment, maintenance and deconstruction of buildings. Digital twins can help to simplify planning and to make processes more efficient. It is in this context that Fraunhofer HHI is researching AI-based methods for automatically generating and using digital twins in construction engineering.

AI methods for digitalization and capturing of as-built status

Most of today's construction work is carried out on buildings that already exist. Whilst there are usually large amounts of raw data available for these buildings, these data are often not sufficiently digitized or they are inconsistent, or high-quality building information modelling (BIM) is not available. The goal of the BIMKIT research project (the name of which is based on the German for as-built modelling of buildings and infrastructure projects using AI to generate digital twins), supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK), is therefore to make use of AI methods to convert multimodal raw data into detailed BIM models either automatically or using supporting tools. This involves making equal use of, on the one hand, 2D plans in vector or raster format, images and 3D point clouds of the current structures and, on the other hand, documents and files on their construction, operation and maintenance. Within its modular system, individual modules equipped with specialized neural networks carry out partial tasks, the results of which are then merged and validated or supplemented with expert knowledge.

Here, Fraunhofer HHI is contributing its expertise in machine learning-based image analysis in order to extract high-quality information from plans, images and point clouds and then generate detailed 3D models from that information. New methods in geometric reconstruction allow quick live capturing of spaces to be performed via mobile devices or stereo cameras, which can be integrated into a helmet for instance. In addition to geometric information, AI processes can clean up raw data or carry out semantic segmentation, i.e. allocate the 3D points or pixels to semantic categories (e.g. door, wall, window, fitting, etc.). Similarly, computer-aided design plan data can be analyzed and expanded into semantically enriched models. The relationships between plan data and photos of parts of buildings can be established using a new type of 2D-3D registration that works using semantic similarities and the position within the plan where the image is taken. Material classifications in the captured data enrich the model further. These form the basis for sound simulations that can be used to evaluate the room and architectural acoustic properties within the digital twin.

Digital twins for assembly support

The uses of digital twins are not restricted to planning processes. They can also be used to support assembly and construction of new structures. The goal of the DigitalTwin project, supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), is to use digital tools to create a more effective network between individual participants along the entire value chain. Using extended reality (XR) glasses, additional information can be blended into the user's line of sight in sync with their physical view. This allows data from the digital twin to be visualized within the specific context. In the other direction, data about working processes captured via cameras on site are then reflected in the digital model. The interface is an XR visualization framework developed at Fraunhofer HHI and offers extensive customization options.

In one practical application case, project partner seele used the system to support the assembly of steel-glass facade structures. One challenge here is the geometric similarity of the individual steel node elements that give the spherical grid shell structures their shape. To overcome this similarity and identify the nodes, an AI-based combined localization, classification and angle-estimation system for 3D objects was developed from 2D images. What makes this approach unique is that the annotated training data for the neural network were generated entirely synthetically. This means that it can be easily and automatically extended for new objects. The process is able to track multiple objects in terms of their position in the 3D space simultaneously and in real time, which means, for example, that the progress of the construction can be logged. During the assembly, arrow inscriptions in the AR glasses indicate at what point and in what orientation an object needs to be positioned, which saves time and reduces the risk of assembly errors. As part of the DigitalTwin project, assembly support was provided for an entire construction using a 3D-printed grid shell model. An interactive demonstration is currently being set up in the Forum Digital Technologies in Berlin.

> Hardware-optimized systems, efficient coding processes and special distributed learning methods using resource-saving devices are being developed in order to reduce the energy consumption of AI processes.

Green AI

Increasing the efficiency of AI-specific algorithms and processes is taking on a special significance in the context of worldwide efforts to reduce CO_2 emissions. Artificial intelligence is currently being deployed in many important areas and is constantly entering new fields of application. The neural networks have become increasingly complex in recent years and typically require significant processing power to train and run, which means they come with major energy requirements. In addition, there has been an expansion of distributed learning processes, requiring increasing amounts of data to be transmitted regularly in the form of parameter updates for deep neural networks.

Energy-efficient AI at Fraunhofer HHI

As part of the focus topic "Green AI," Fraunhofer HHI is developing solutions to reduce the energy requirements of AI applications. This includes methods that make neural networks, and therefore AI, more energy-efficient to train, apply and transmit. These methods include hardware-optimized systems to lower the energy requirements of running AI models, distributed learning processes and coding algorithms to increase the efficiency of transmitting neural networks. Fraunhofer HHI is cooperating with various partners on this point, such as *dena* (Deutsche Energie-Agentur GmbH), and companies using AI applications in data centers and other institutions as part of projects focusing on energy-efficient AI. It is also participating in international standardization initiatives for neural network coding.

CO_2-reduced AI in data centers

Developing special hardware for running neural networks with less energy is a major topic. These methods are specially designed for data centers in order to reduce the CO_2 footprint of today's complex AI processes, such as data classification using neural networks. Currently, data centers mainly use systems consisting of host computers or workstations, connected to a number of specialized processing accelerators such as graphics cards (GPUs), which therefore require a significant amount of energy to carry out the processing. As an alternative, Fraunhofer HHI is developing special processing accelerators that are based on field-programmable gate arrays (FPGAs) and are directly connected to the network of a data center via a network interface. This yields energy savings of up to 70%, thanks firstly to the FGPA architecture and secondly to the autonomous accelerator architecture (known as a "network attached accelerator" or NAA), which does not require a host. The FPGAs are specifically configured for an individual neural network, thereby minimizing their energy consumption compared to a GPU.

Distributed AI

Another major research area is the development of distributed AI systems, focusing in particular on energy efficiency. Distributed learning systems are particularly useful in application areas that are subject to strict data protection requirements. This is because (unlike the centralized learning approach), the only data exchanged are the parameters of the neural network. This means, for instance, a business unit that handles sensitive data can train a shared neural network and use it for further data analysis without having to give away its local data. For example, several hospitals can train a network on their own local computerized tomography (CT) data and create a joint neural network that has greater diagnostic power (e.g. in identifying tumor cells) and is shared by all the participants, but without having to share their CT data.

In addition, distributed learning systems can offer potential energy savings compared to carrying out centralized training in large data centers. This is because distributed learning normally takes place on low-resource devices, therefore doing away with the need for energy-intensive cooling. Accordingly, Fraunhofer HHI is focusing efforts on developing federated learning methods, where the local learning process is specially adapted to the client devices being used and, once trained, the parameters of the neural networks are transmitted efficiently.

Standardized AI coding and transmission

An important element of energy-efficient distributed AI processes is the efficient transmission of the neural network parameters. Neural network updates need to be transmitted frequently, particularly during the training processes. Consequently, Fraunhofer HHI has in recent years developed efficient coding procedures for compressing neural networks and has been working since 2019 on the international standardization of these processes as part of the ISO/IEC MPEG committee. This led to the creation of the NNC standard (Neural Network Coding — ISO/IEC 15938-17), to which Fraunhofer HHI contributed two thirds of the underlying technologies, e.g. DeepCABAC, a particularly efficient coding method. The NNC standard can be used to compress neural networks to a fraction of their original size (e.g. <5% for a VGG16 network), without losing any of the classification precision. A second edition of the NNC standard is currently being developed specifically for updates to neural networks, which will allow further bitrate savings to be achieved.

Feasibility studies showed that the NNC standard also helps to reduce energy consumption, e.g. in distributed learning environments. Here, a net energy saving can be achieved, as transmitting heavily compressed neural networks saves significantly more energy than has to be expended for the additional encoding and decoding required.

"

Data-driven approaches are being used to design new types of video coding processes with increasing success.“

Dr.-Ing. Detlev Marpe,
Video Communication and Applications

AI-based video coding

Communicating via video conferences, video streaming or in new formats such as virtual or augmented reality is a permanent fixture of everyday life in modern connected societies. The scale of video data that have to be transmitted all over the world for these sorts of applications is constantly increasing. Given the limited bandwidth available within the transmission channels, there is an urgent need for ways to improve the efficiency of video-data coding.

In the Video Communication and Applications (VCA) department, video-coding algorithms are being developed in order to improve coding efficiency compared to the state-of-the-art video-coding standard Versatile Video Coding (VVC). Data-driven methods are increasingly being used to design these algorithms. Three examples are presented below in more detail to illustrate the current research activities being carried out by the department in this area.

Combined intra- and inter-production

Predictive coding is a key component of modern hybrid block-based video codecs. This involves using previously reconstructed samples to generate a signal prediction for a block within an image of a video sequence that needs to be coded. The VCA department is working on more efficient prediction processes for video compression in order to reduce the bitrate of the prediction errors that need to be transmitted. In modern video codecs, a block is predicted on the basis either of neighboring samples within the same image or of samples from another previously decoded image. The first option is referred to as intra-prediction and the latter as inter-prediction. In order to achieve noise reduction, inter-prediction is commonly carried out by averaging two individual prediction signals, a process known as bi-prediction. The prediction method being developed in the VCA department combines intra- and inter-prediction. To do this, the prediction signal is generated using a convolutional network which processes both the individual inter-prediction signals from the bi-prediction process and the neighboring reconstructed samples of a block together. This new prediction method has been shown to be capable of significantly reducing the prediction errors in the original inter-prediction signals. It has been integrated as a prediction method into the framework of the VVC codec where it yields significant coding gains.

Data-driven design of in-loop filters

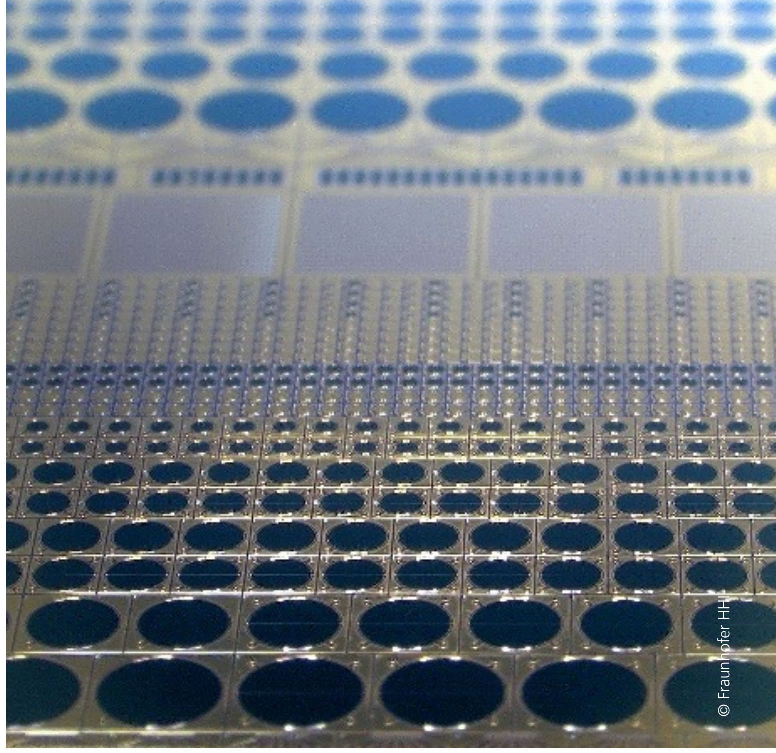
When decoding a video signal, errors can occur once the prediction signal and the reconstructed residual error have been added together. The temporal prediction applied between the images can significantly increase these errors. For this reason, today's video codecs contain specific signal adjustments, known as "in-loop filters," that are applied to individual images within a video sequence before they are displayed or used to predict further images. One of the defining characteristics of the VVC standard is that it contains a large amount of coding options, such as numerous combinations of different transformations and prediction methods. It would be difficult to describe and minimize all of the coding artifacts that may result from these many and varied coding processes.

To deal with this issue, the VCA department took a data-driven approach in order to develop an in-loop filter for a VVC-based codec. Under this approach, signal adjustments are applied to an image based on a weighted sum of FIR filters. The weighting varies for each sample and is calculated from the signal using a convolutional network. It can therefore be interpreted as an indicator of whether a sample belongs to various classes of coding artifact. The in-loop filter developed by Fraunhofer HHI can achieve significant coding gains against the VVC standard. Compared to other approaches, this new method is significantly less complex. Furthermore, splitting the process into classification and filtering provides an interpretable architecture for convolution-based in-loop filters.

Vector quantization and motion representation in end-to-end compression

The core principle of what is known as "end-to-end" compression is using non-linear transformations to code certain types of input signals. To transmit a signal, the transform coefficients are quantized and the quantization indices are transmitted. It is well established that vector quantization is the only way of achieving optimal quantization of the transform coefficients. However, as the transforms applied in end-to-end compression are not orthogonal and are not even linear, more efficient quantization of the transform coefficients does not automatically lead to more efficient transmission of the original signals. Despite this, the VCA department has successfully configured and modified the learning algorithm for determining non-linear transforms when applying vector quantization. This method yields significant coding gains compared to existing end-to-end image compression processes.

Another key research focus in the VCA department is the development of efficient motion representations for use in end-to-end approaches to video coding. This involves describing and transmitting the motion fields in order to predict an image based on a prior image. The first video codec based on this concept has been successfully created.



Quantum key distribution at Fraunhofer HHI

The challenges associated with future-proof and long-term data security are only continuing to grow. In response to which Fraunhofer HHI is working to develop innovative solutions for quantum key distribution (QKD). These were successfully demonstrated in the first quantum-secured video conference between two German Federal authorities.

Optimizing quantum technologies for specific applications

Fraunhofer HHI's Photonic Networks and Systems and Photonic Components departments are working on a large number of projects with partners in research, industry and authorities on systems, components and concepts for quantum-secured communication networks. One key area of these projects is adapting the quantum key distribution process to the specific requirements of different application scenarios and ensuring it is seamlessly integrated into existing infrastructures. As one of the four central institutes involved in the QuNET initiative, Fraunhofer HHI has implemented a modular development platform based on the time-phase-encoded BB84-QKD protocol. This allows new technologies and applications to be integrated incrementally and rapidly, and to be demonstrated in lab and field experiments. Fraunhofer HHI's QKD system delivered highly secure keys over the course of several weeks to the offices of the German Federal Ministry of Education and Research (BMBF) and the German Federal Office for Information Security (BSI) in Bonn, the first practical example of a typical application case for quantum key distribution. This enabled these two Federal authorities to conduct their first quantum-secured video conference.

Increased key rates for future quantum backbones

Modern optical fiber networks allow a large number of communication channels of different wavelengths to be transmitted at the same time. Fraunhofer HHI is investigating to what extent this approach can be used to increase transmission rates in quantum communication. Working with university and industry partners, up to 11 QKD channels were transmitted simultaneously via a shared fiber. Thanks to a rapid Field Programmable Gate Array (FPGA) evaluation process developed at Fraunhofer HHI, a key rate of over 14 Mbit/s was achieved, paving the way for highly secure quantum backbones between metropolitan regions in future. In addition, the simultaneous transfer of a quantum channel and traditional communication channels via a single shared fiber was successfully demonstrated using Fraunhofer HHI's QKD development platform.

Left: Federal Minister Anja Karliczek and Fraunhofer HHI Executive Director Prof. Martin Schell during the quantum-secured video-conference; center: installation of Fraunhofer HHI's QKD system at the Bonn office of the German Federal Ministry of Education and Research (BMBF); right: individual photon detectors based on InP semiconductors and developed at Fraunhofer HHI

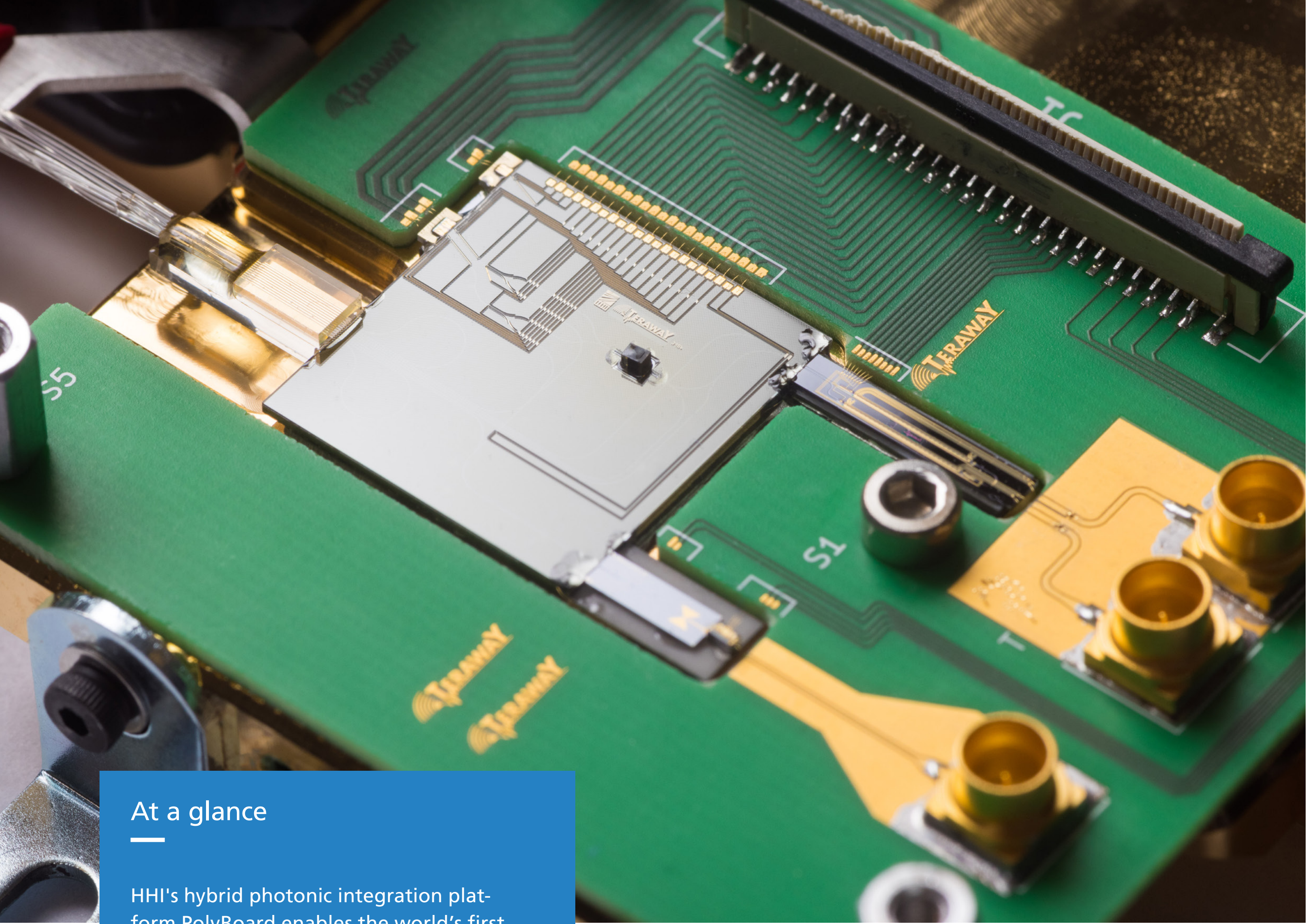
Key technologies for quantum repeaters

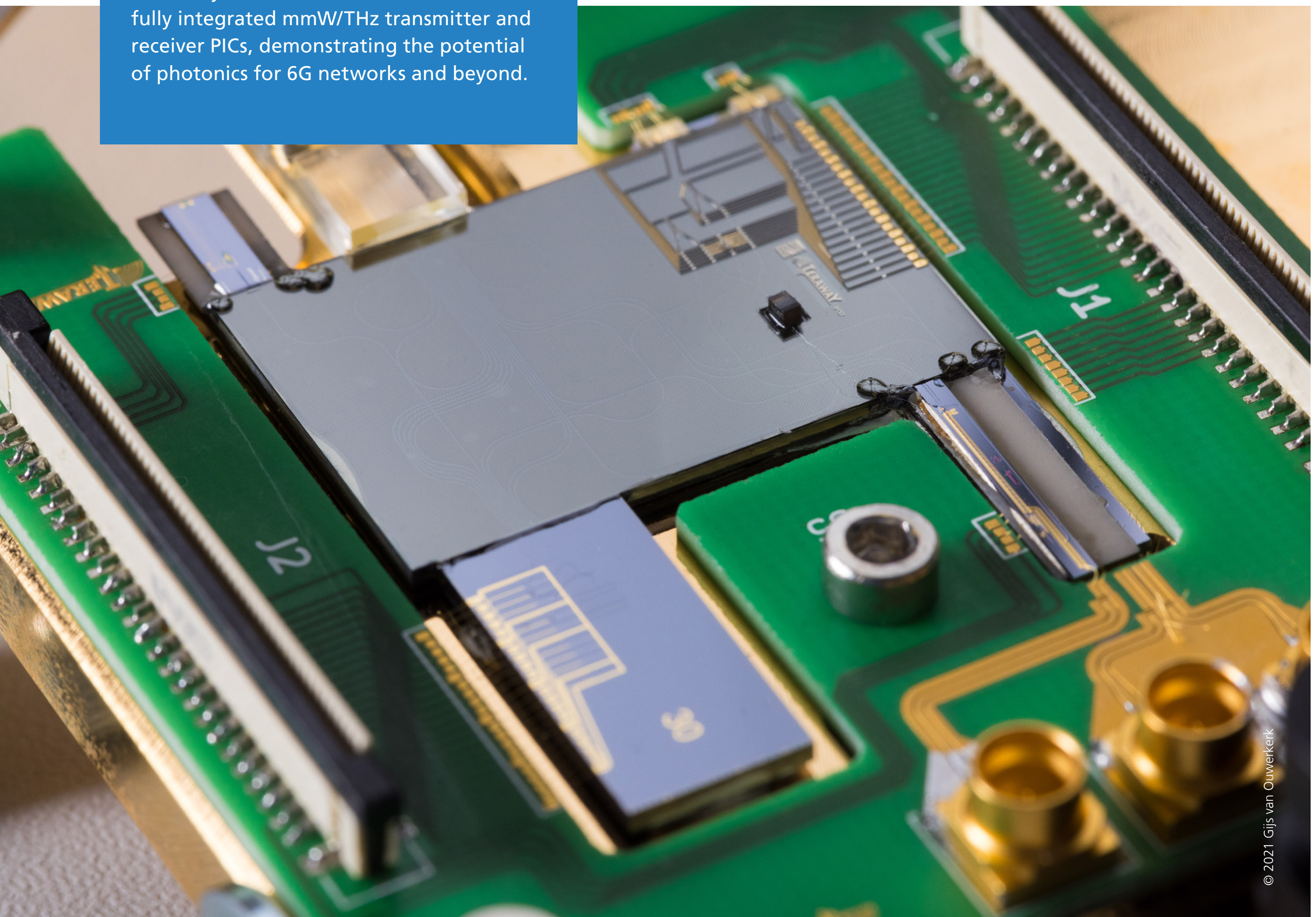
As one of the 26 members of Project QR.X, Fraunhofer HHI has also been working towards overcoming the current technical limitations on the distances over which quantum communication can operate by enhancing its own innovative key technologies for devices called "quantum repeaters." Fraunhofer HHI is also developing an entanglement-based quantum communication system in order to allow quantum teleportation experiments to be conducted with partners. This will play a key role in any future quantum repeater architecture. The institute is also permanently expanding its fiber testbed using a hybrid connection to a fiber-coupled free-space link. This will allow the designs and modules developed within the group to be tested.

High-performance detectors for quantum communication

As part of the QuNET initiative, funded by the German Federal Ministry of Education and Research (BMBF), the necessary hardware components are also being developed at Fraunhofer HHI. A piece of technology called a "single photon avalanche diode" (SPAD) is of relevance for exchanging quantum keys. These InP components allow individual photons to be detected. Unlike superconducting nanowire single photon detectors, SPADs do not require extremely low temperatures to operate. This means that they are particularly suitable for use in quantum communication networks. The detector group, led by Dr. Patrick Runge, has made significant progress in SPAD development and, after a three-year development phase, is in a position to demonstrate high-performance components.

The SPADs developed at Fraunhofer HHI are competitive in terms of characteristics such as detection efficiency, dark count rates, afterpulsing probability and jitter. As a critical component in the field of quantum key exchange, they represent a further element of Germany's technological independence as a quantum communication hub. The next anticipated stage of the QuNET initiative is to deploy the SPADs developed at Fraunhofer HHI in the systems developed by the Photonic Networks and Systems department.





At a glance

HHI's hybrid photonic integration platform PolyBoard enables the world's first fully integrated mmW/THz transmitter and receiver PICs, demonstrating the potential of photonics for 6G networks and beyond.

Hybrid photonic integrated circuits for 6G wireless networks and beyond

The Hybrid PICs group, in cooperation with the InP Foundry and the THz Sensors and Systems group, has demonstrated for the first time fully integrated photonic wireless transceivers that pave the way towards the use of photonics in 6G and beyond wireless networks.

Using the most appropriate material systems for the photonic functional building blocks

Photonic generation of mm-wave (mmW) and THz frequency signals is key for wireless communications in 6G and beyond due to the high bit rates that can be achieved with photonic components. Numerous transmitter and receiver demonstrators have been reported in the literature that use separately packaged lasers, modulators, and photonic THz transmitters and receivers, making these systems bulky and limiting their implementation in network devices. Moreover, to stabilize the laser sources, e.g. to obtain a mmW/THz carrier with high stability and spectral purity, injection locking schemes based on optical frequency combs and fiber-based optical isolators or circulators are typically employed, adding bulkiness and complexity.

The European project entitled *Terahertz Technology for Ultra-broadband and Ultra-wideband Operation of Backhaul and Fronthaul Links in Systems with SDN Management of Network and Radio Resources* (TERAWAY) demonstrated fully integrated mmW/THz transmitter and receiver PICs for wireless communications based on Fraunhofer HHI's hybrid photonic integration platform PolyBoard, addressing miniaturization challenges by using the most appropriate material system for a photonic functional component. The PolyBoard includes, for example, tunable lasers and optical isolators for optical signal generation and on-chip implementation of the injection-locking scheme (see top figure at left). InP-based modulator PICs from Fraunhofer HHI's InP foundry enable the generation of optical frequency combs to stabilize the laser frequency and modulate the data signal. In the emitter PIC, SiN-based optical filters fabricated by the Dutch partner LioniX allow for single sideband operation and Fraunhofer HHI's InP-based photonic Terahertz transmitters and receivers are used for photonic generation and detection of radio signals (see bottom figure at left). The chiplets were partially assembled at Fraunhofer HHI and finally packaged by the Dutch company PHIX, demonstrating for the first time fully integrated photonic wireless transmitter and receiver modules for 6G networks and beyond.

What is next?

In the coming generations of photonic wireless emitter and receiver PICs, the number of lasers and modulators will be increased to generate multiple wireless signals at different frequencies. In addition, arrays of photonic transmitters and receivers will be incorporated to allow for optical beam steering to provide the possibility of aligning the wireless links and targeting moving nodes (e.g. drones).

Left: Hybrid-integrated photonic mmWave/THz transmitter and receiver PICs for communication in wireless 6G networks

Research for the energy transition: CO_2-neutral real-world lab for preparing, recycling and safety of lithium-ion batteries

Left: battery abuse test; center: long-term battery-cycle tests; right: electrical fishing boat

Fraunhofer HHI's CO_2-neutral real-world lab is conducting thermal and electrical abuse tests of lithium-ion batteries capable of storing up to 150 kWh. These investigations focus on a wide variety of safety considerations for mobile and stationary applications and the associated systems for recycling the lithium batteries used in electric transportation (second-life batteries). For example, modular container-based mini-grid systems used for the decentralized supply of energy in developing countries have been developed at Fraunhofer HHI and have already been deployed in on-site pilot studies.

Lithium-ion batteries (LIB) are currently the main energy sources in both electromobility and in stationary storage. They can play a key role in ensuring the stability of the network or they can supplement photovoltaic equipment on a private or industrial scale. Successful economic implementation of these storage systems places special demands on the associated safety concepts, including the extinguishing agents required in the event of an accident. LIBs store large amounts of energy, but they are also sometimes susceptible to the smallest technical fault or inexpert handling, leading to uncontrolled discharge of the chemically stored energy. In the worst-case scenario, this can result in fire and/or explosion. In Fraunhofer HHI's real-world lab at the Goslar site, thermically and electrically induced abuse tests are being carried out under predefined conditions. One of the primary goals is to develop new safety and extinguishing systems based on innovative sensors. Another is to test established safety solutions in collaboration with industrial partners and to certify them in cooperation with the Association for Electrical, Electronic and Information Technologies (VDE). In addition to storage modules capable of holding up to 150 kWh, transportation and storage containers for LIBs and extinguishing agents and equipment are being tested, and long-term battery-cycle tests are being carried out.

What makes Fraunhofer HHI's real-world lab unique is that it replicates the equipment's entire energy supply process, including the exhaust gas treatment system via photovoltaics and a large lithium-ion store. This storage is comprised exclusively of what are referred to as "second-life photovoltaic (PV) modules" and "second-life LIBs." This approach exemplifies how CO_2 emissions can be reduced in the development and testing of LIBs. As such, it also makes a valuable contribution to the circular economy by reusing used PV modules and LIBs in an ecologically and economically appropriate process that closely replicates industrial practice. So far, little attention has been paid to combining second-life LIBs with second-life photovoltaics to create what are referred to as "mini-grid systems" for the decentralized supply of energy in developing countries. According to official estimates, approximately 86% of people in the rural areas of Sub-Saharan Africa have no access to electricity. The International Energy Agency (IEA) expects that by 2040 approximately 140 million people in Sub-Saharan African could be supplied with power via mini-grids. In addition to improving the quality of life for these populations, having access to electricity is the most important prerequisite for local development, particularly in terms of accessing clean drinking water. To this end, Fraunhofer HHI has been working with the start-up VoltaView GmbH to develop a modular container-based mini-grid system for the decentralized supply of power and treatment of drinking water.

The first of these systems was financed by the UK-based NextEnergy Foundation and will be installed in Tanzania to supply a school with electricity and drinking water in November 2022. Further systems are being constructed and will be installed in western Africa (Gambia) at the end of 2022. In addition to providing drinking water, the mini-grids can also be used as a charging station for mobile portable LIB packs (battery-to-go with an energy capacity of 3 kWh). These can be used to provide households with electricity or as an energy source for electrically powered fishing boats. A major advantage of this technology is that it does not require any elaborate infrastructure. Working with the *University of Gambia* and supported by the *United Nations Industrial Development Organization*, an initial pilot project has been set up on the island of Jinack in Gambia.

Container-based mini-grid system with battery-charging service and provision of drinking-water.

> **Light is becoming an increasingly important medium for wireless communication.
> LiFi systems behave like cables; they are secure and provide high data rates, low latency and high reliability.**

LiFi

Humans have been sending messages by light since the dawn of history, using lighthouses or sending Morse code via light over distances of several kilometers. The optical spectrum has been used for fiber optic communications since 1965.

In the 21st century, visible and near-infrared light is also being used for wireless communication in indoor spaces, achieving speeds measured in gigabits per second. Adapted from the term wireless fidelity (WiFi) this technology is referred to as light fidelity (LiFi). LiFi provides an alternative way of achieving wireless communication in environments where there are challenges to using radio technologies. Light can even be used to communicate wirelessly and within environments affected by significant electromagnetic interference, such as in industrial production contexts or when using sensitive measuring devices in a medical context.

Fraunhofer HHI was involved in the earliest LiFi demonstrations and has continued to steadily develop the technology ever since. LiFi makes it possible to use large additional spectrums in order to, relieving the burden on the overcrowded radio spectrum. Expanding the network to include several LiFi cells can provide access to the highest data rates for all users. LiFi is of international interest as a new optical air interface solution in the context of 6G, but it can make a significant contribution to digital transformation in many areas. Fraunhofer HHI's constant efforts, combined with its close partnerships worldwide, are enhancing Germany's and Europe's technological leadership in this area.

Supported by LiFi: digital transformation in medicine and industry

Digital transformation is a key topic in all areas of life. This includes medicine, where the use of digital technology is becoming ever more important. Unlike in an office or at home, robust and secure wireless communication is essential here. Examples include the seamless logging of a patient's journey from the site of an accident to the operating room or the provision of high-resolution imaging content during treatment. In these types of application, LiFi can help to improve health provision in smart hospitals.

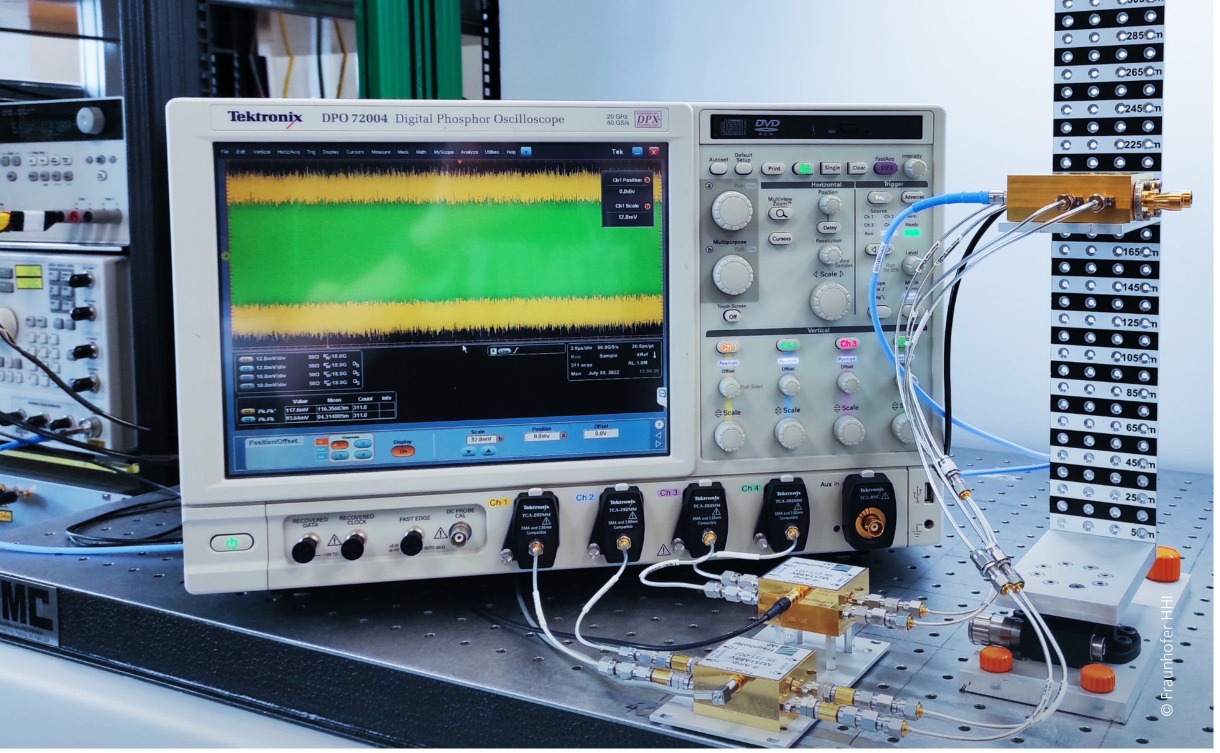
As part of the LiFi-enabled 5G for Industrial and Medical Networks (LINCNET) project, which was created in collaboration with the Carl Thiem Clinic in Cottbus and other project partners, tailored LiFi solutions are being developed to meet the requirements of medical and industrial settings. The goal is to pave the way for comprehensive deployment in these areas. In hospitals in particular, sensitive measuring devices are in constant use. These make it harder to use current or even future radio-based transmission technologies. There are also some hospital departments, such as radiology, that cannot use radio communication because of their design and the X-ray shielding in the walls. LiFi can offer a realistic alternative in this case. There are particularly extensive data-security requirements due to the sensitive nature of patients' medical data. LiFi networks are very easy to protect as the data remain within the light beam and never go beyond precisely where they are needed. They cannot be intercepted from outside. In addition, there are plans to develop methods for simplifying LiFi installation and to investigate new optical sources that can achieve high data rates.

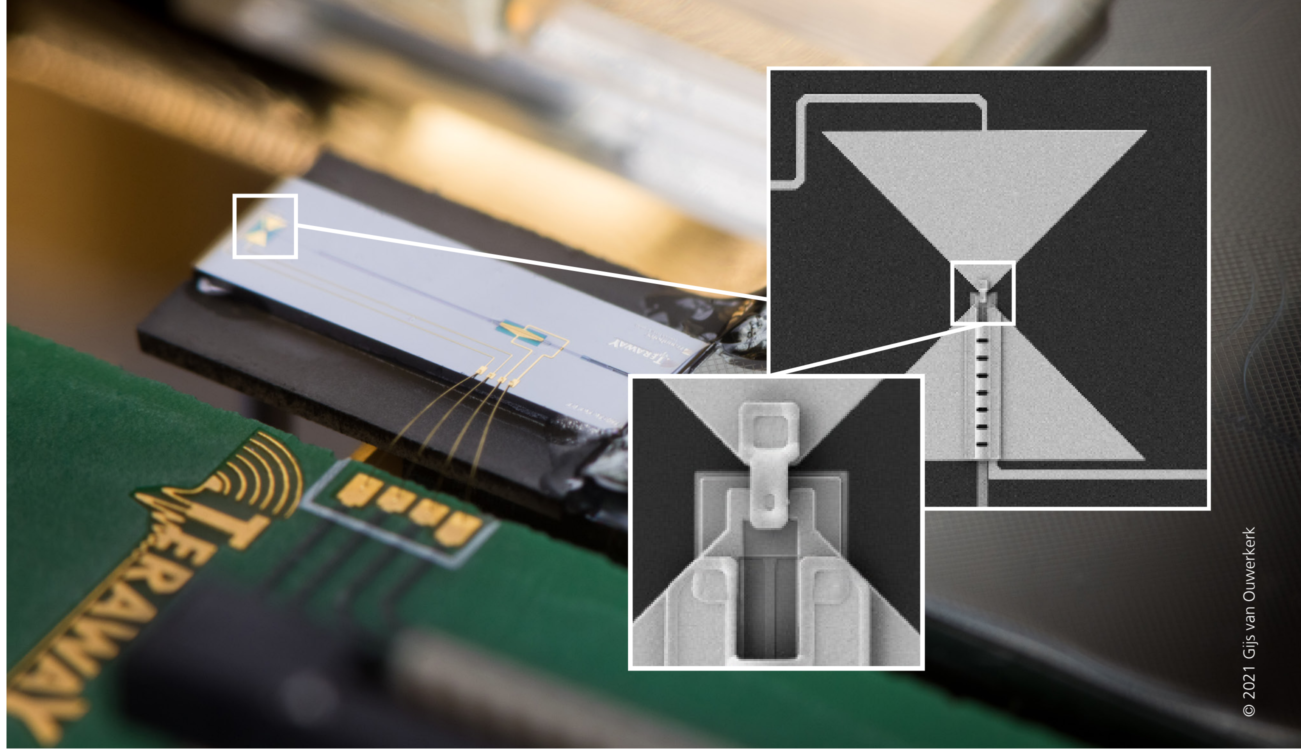
LiFi for applications in buildings

LiFi is also an attractive option for use in buildings due to the applications that will form part of the future internet of things and the resulting high data rates that will be required per user. Augmented and virtual reality are becoming a more regular feature in the home and require high-speed and stable wireless communication. LiFi hotspots with exclusive media access and extremely high data density can be used to supplement existing radio technologies such as WiFi. One advantage is that the optical spectrum is not susceptible to interference from existing radio-based systems, such as the many neighboring WiFi networks or Bluetooth speakers. LiFi can be retrofitted anywhere and cannot pass through walls, which provides additional data security. The vision is to use the future lighting infrastructure as a distribution network for LiFi. The first demonstrations of a powerline communication and LiFi combination have already highlighted the potential of this approach.

Fraunhofer HHI LiFi system with Gbit/s data rates

Top left: using LiFi for point-to-point networking of buildings, smart cities and fixed wireless access applications; top right: robust vehicle-to-vehicle communication using LiFi





THz communication for future 6G networks

– from optoelectronic components to field-ready systems

Left: laboratory setup of a THz receiver unit; center: model of a dual-aperture THz antenna; right: hybrid integrated photonic THz transmitter unit from the TERAWAY project

Applications like Industry 4.0, autonomous driving, smart cities and augmented reality will require extremely large bandwidths in the future. These bandwidths can be achieved with THz wireless communication. As it uses frequencies above those in 4G LTE and 5G mobile networks, this technology can easily slot into existing communication networks. It could potentially provide data rates a hundred times greater than 5G.

Technologies for frequency ranges above 100 GHz for wireless THz communication are currently a focal point of research and development all over the world. They are considered a key technology for fulfilling the ambitious performance targets of future 6G networks. These networks are expected to facilitate a massive increase in wireless data rates, a significant reduction in latency and an improvement in reliability and network coverage compared to today’s 5G networks.

Optoelectronic components for THz communication

Fraunhofer HHI is conducting research across the field of THz communication in various working groups. The Terahertz Sensor Systems group within the Photonic Components department is focusing on developing transmitter and receiver units for use in this special frequency range. The group is building on many years of experience in developing photonic components for glass-fiber-based telecommunications. The solutions developed in this area are now being further developed for use in THz communication.

THz transmitters based on ultrasonic photodiodes

Ultrasonic photodiodes produced through Fraunhofer HHI’s advanced InP process line are being used as optoelectronic THz transmitters. Within these photodiodes, an optical beat signal consisting of two slightly diverging laser lines are directly converted into a THz beam (photomixing). This allows a single THz transmitter to cover a very wide frequency range (0.1 THz to 4.5 THz). In order to transmit the data, the amplitude/phase of one of the laser lines is modulated to send the data signal at the THz carrier frequency. With the coherent operating mode, complex modulation formats such as quadrature amplitude modulation (QAM) or quaternary phase-shift keying (QPSK) can be used, and data rates of >100 Gb/s have already been demonstrated.

Photomixers as coherent THz receivers

Devices referred to as “photomixers” are being further developed as THz receivers for the purposes of data transmission. These are based on special ultrasonic semiconductor materials that are manufactured at Fraunhofer HHI using molecular-beam epitaxy. These photomixers are also stimulated using an optical beat signal that is mixed with the incoming THz beam. If there is a difference between the frequency of the optical beat and that of the THz signal (heterodyne detection), the mix results in an intermediate frequency, which is used to demodulate the data.

Photonic integration of THz systems

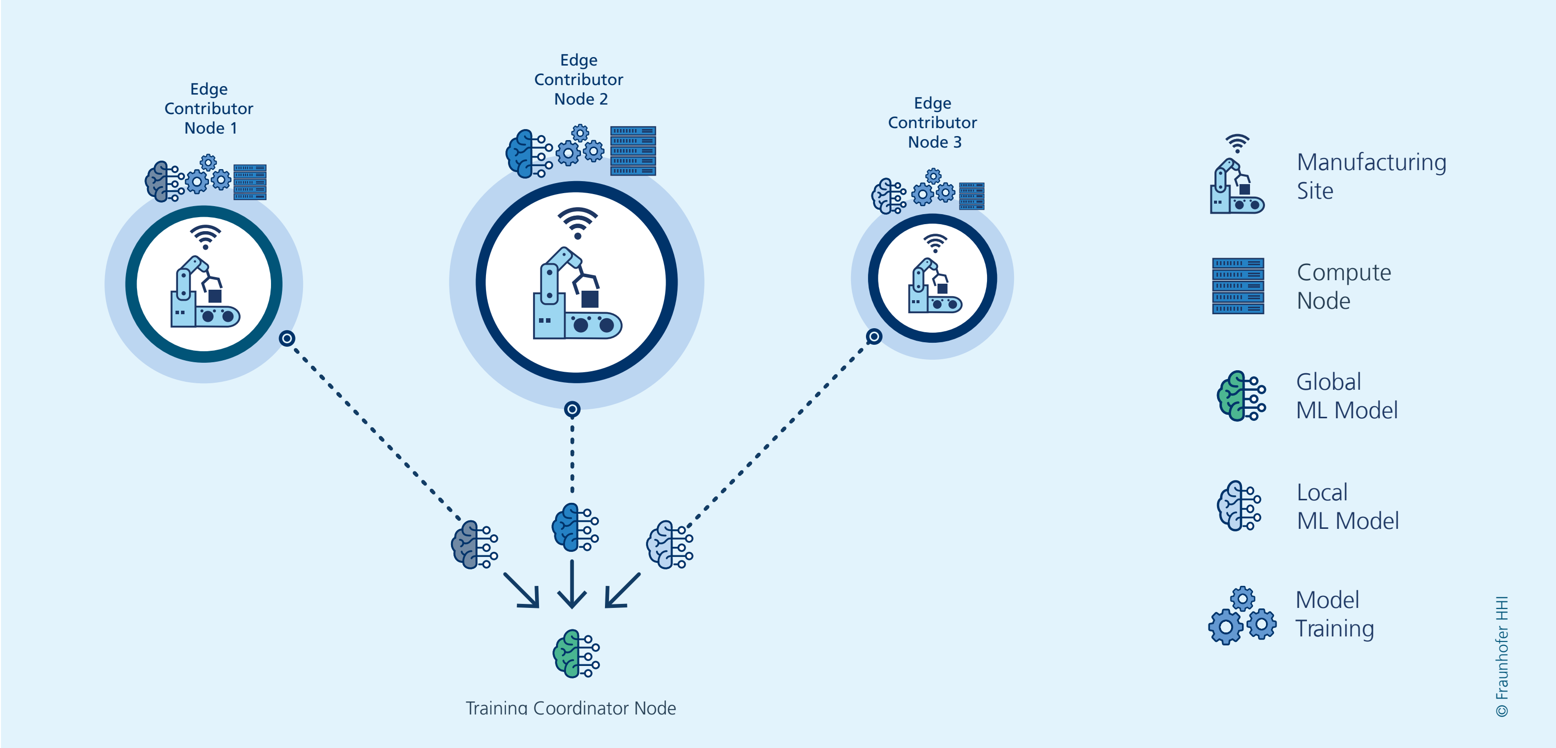
Photonic integration provides significant potential for further miniaturization of optoelectronic THz systems, because all of the components required in this sort of system, such as lasers and photodiodes, can be manufactured using Fraunhofer HHI’s InP technology. Various EU projects, including Non-contact Millimeter and Terahertz Frequency Measurement Paradigm for Instrumentation and Sensing Applications Unlocking Metrology-grade Results (TERAmeasure) and TERAWAY are currently working intensively on this challenge.

Wide-band THz communication

The Submarine and Core Systems group within the Photonic Networks and Systems department is looking into transmitting very high data rates through the wireless THz channel and integrating THz links into the existing (fiber-optic) infrastructure. An important milestone towards early market introduction was reached as part of the TERRANOVA and Convergent Networks (KoNET) projects in the form of the world’s first real-time data transmission through a stretch of combined fiber-optic and THz-wireless segments using a commercial 100 Gb/s modem. In field tests at the campus of TU Berlin, error-free transmission of a 100 Gb/s data signal was also achieved across a stretch of 500 m.

Development of field-ready THz prototypes

Working with the Fraunhofer Institute for Applied Solid State Physics IAF in Freiburg, the Submarine and Core Systems group is currently developing a field-ready prototype for point-to-point THz communication with a carrier frequency of 300 GHz at data rates of up to 100 Gb/s across a stretch of open space of up to 1 km. This prototype, which has been presented at various exhibitions, is equipped with weatherproof housing and a fiber-optic data interface. Initially, it is intended for use in urban fronthaul and backhaul networks to gather information about long-term use in situations that closely replicate the real world.



AI for Photonics and Edge

Artificial intelligence (AI) is transforming almost all industries and is considered a main technological enabler for 5G/6G communication networks. It is also expected to change the status-quo and to revolutionize the functional blocks across the entire stack of optical transport networks, which span from our rooms and offices (Fiber to the Room (FTTR)) to other cities, countries, or continents (metro/core/submarine networks). At Fraunhofer HHI, we develop AI-assisted solutions for the broad ecosystem of optical networks and innovate state-of-the-art algorithms to bring the vision of AI-assisted network automation to reality.

The realization of AI-assisted network automation requires substantial research and developments in several key areas including: 1) network monitoring and programmability, 2) telemetry collection and streaming, 3) reference dataset generation, 4) algorithm development, 5) experimental test and validation, as well as 6) explainability, certification and deployment. These developments should consider the foundational characteristics of the telco ecosystem, which has numerous stakeholders. On the one hand, this requires the incorporation of a high level of interoperability in the development process. On the other hand, as AI-assisted network automation relies heavily on data sharing, this adds an additional level of complexity due to data confidentiality and regulatory issues. These concerns motivate the incorporation of solutions that offer security, trust, and protection of stakeholder privacy.

In the Photonic Networks & Systems department, the Data Analytics and Signal Processing research group carries out research in all of these key areas and beyond. We develop innovative solutions across the entire machine learning (ML) pipeline and validate them using our large-scale test infrastructure. As one of our strategic areas, we perform research on the application of privacy-preserving distributed AI, AI on the edge, and federated learning for telecom networks and other data-centric industries.

Public datasets for network automation

As a primary enabler for network automation, we develop and publish reference datasets for a multitude of use cases (e.g. quality-of-transmission estimation, predictive maintenance, traffic forecast). We already published the first public dataset collection for quality-of-transmission estimation in the community of optical networks. The dataset collection is currently being extended with an experimental measurements focused on multi-band networks covering S+C+L.

Carrier-grade machine learning pipeline for real-time operation

The realization of autonomous networks requires a reliable and high performance ML pipeline. This enables streaming fine-grained monitoring data across the whole infrastructure to run ML-assisted network APPs. We developed a real-time ML pipeline including a telemetry framework with data sovereignty features, a highly scalable data lake, and an analytic module to run ML APPs. We contributed our implementation to the Telemetry Work Item of the European Telecommunications Standards Institute (ETSI) Industry Specification Group (ISG) Fifth Generation Fixed Network (F5G) and performed a successful proof-of-concept demonstration for real-time traffic monitoring and analysis.

The distributed learning framework

The emergence of a data economy and data-centric solutions requires advanced techniques to protect the confidentiality, privacy, and ownership of the data. We are developing a software solution called the Distributed Learning Framework (DLFi) that offers state-of-the-art privacy-preserving algorithms for the realization of AI-based products. DLFi supports different use cases across multiple sectors including telecom, Industry 4.0, and medicine.

Distributed intelligence for industry automation

Edge-Cloud is playing a significant role in the current transformation of industrial automation, where Operational Technologies (OT) and Information Technologies (IT) are converging. The Fraunhofer Edge Cloud (FEC) offers a research platform to test and validate industry 4.0 use cases. FEC offers a virtualization layer based on OpenStack, GPU acceleration, and data sovereignty based on imaging development systems (IDS). We have accomplished several proof-of-concept demonstrations of the FEC together with our partner German Edge Cloud. Moreover, we have successfully demonstrated DLFi in a Kubernetes based deployment on FEC to carry out federated learning sessions for training a YOLOv5 model for visual inspection.

B – Berlin
G – Goslar

Organizational plan

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Dipl.-Betriebsw., MBA
Michael Klee

Quality Management and Safety
Dipl.-Ing. (FH) Mario Perkowski

Corporate Communications
M. A. Martina Müller

Executive Directors

Prof. Dr.-Ing.
Thomas Wiegand
Executive Director

Prof. Dr. rer. nat.
Martin Schell
Executive Director

Division Video
Dr. Ing. Ralf Schäfer

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Dr.-Ing. Thomas Haustein

- System Level Innovations – Dr.-Ing. Lars Thiele
- Technologies and Standards – Dr.-Ing. Thomas Haustein
- Signal and Information Processing – Dr.-Ing. Martin Kasparick
- Optimization and Learning for Communications – Dr. phil. nat. Renato Cavalcante
- Smart Wireless Connectivity – Dr.-Ing. Zoran Utkovski
- mm-Wave – Dr.-Ing. Michael Peter
- Intelligent Network Architecture – Dr.-Ing. Julius Schulz-Zander
- Prototype Development and Systems Integration – Dipl. Ing. (FH) Andreas Forck

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Dr.-Ing. Thomas Schierl

- Multimedia Communications – Dr.-Ing. Cornelius Hellge; Dr.-Ing. Thomas Schierl
- Video Coding Technologies – Dr. rer. nat. Jonathan Pfaff; Prof. Dr.-Ing. Heiko Schwarz
- Embedded Systems – Prof. Dr.-Ing. Benno Stabernack
- Video Coding Systems – Dipl.-Ing. Benjamin Bross; Dipl.-Ing. Adam Wieckowski

Vision and Imaging Technologies (B)
Prof. Dr.-Ing. Peter Eisert
Dr.-Ing. Anna Hilsmann

- Computer Vision and Graphics – Dr.-Ing. Anna Hilsmann
- Immersive Media & Communication – Dipl.-Ing. Ingo Feldmann; PD Dr.-Ing. Oliver Schreer
- Capture and Display Systems – Dipl.-Ing. Christian Weißig
- Interactive and Cognitive Systems – Dr.-Ing. Sebastian Bosse

Artificial Intelligence (B)
Prof. Dr. rer. nat. Wojciech Samek

- Explainable AI – Prof. Dr. rer. nat. Wojciech Samek; Dr. rer. nat. Sebastian Lapuschkin
- Applied Machine Learning – Dr. rer. nat. Jackie Ma
- Efficient Deep Learning – Dr.-Ing. Karsten Müller

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- Detectors and Modulators – Dr.-Ing. Patrick Runge
- Lasers – Dr. rer. nat. Martin Möhrle
- Photonic InP Foundry – Dipl.-Phys. Klemens Janiak
- Hybrid PICs – Dipl.-Ing. Norbert Keil
- Terahertz Sensors and Systems – Dr. rer. nat. Robert Kohlhaas
- Epitaxy – Dr. rer. nat. Christoph Hums
- Processing – Dr. rer. nat. Kristijan Posilovic
- Backend – M. Sc. Maximilian Herzog
- Packaging – B. Sc. Felix Ganzer
- Equipment Operations – Dipl. Ing. Clemens Kleimann

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- FiberLab – Dr. rer. nat. Martin Angelmahr
- Battery Sensor Technology – Dr. rer. nat. Antonio Nedjalkov
- Surface Processing – apl. Prof. Dr. Eike G. Hübner

Photonic Networks and Systems (B)
Prof. Dr.-Ing. Ronald Freund

- Submarine and Core Systems – Dr. rer. nat. Colja Schubert
- Metro, Access and In-house Systems – Prof. Dr. rer. nat. habil. Volker Jungnickel
- Free-Space Optical Systems – Dr.-Ing. Nicolas Perlot
- Digital Signal Processing – Dr.-Ing. Johannes Fischer

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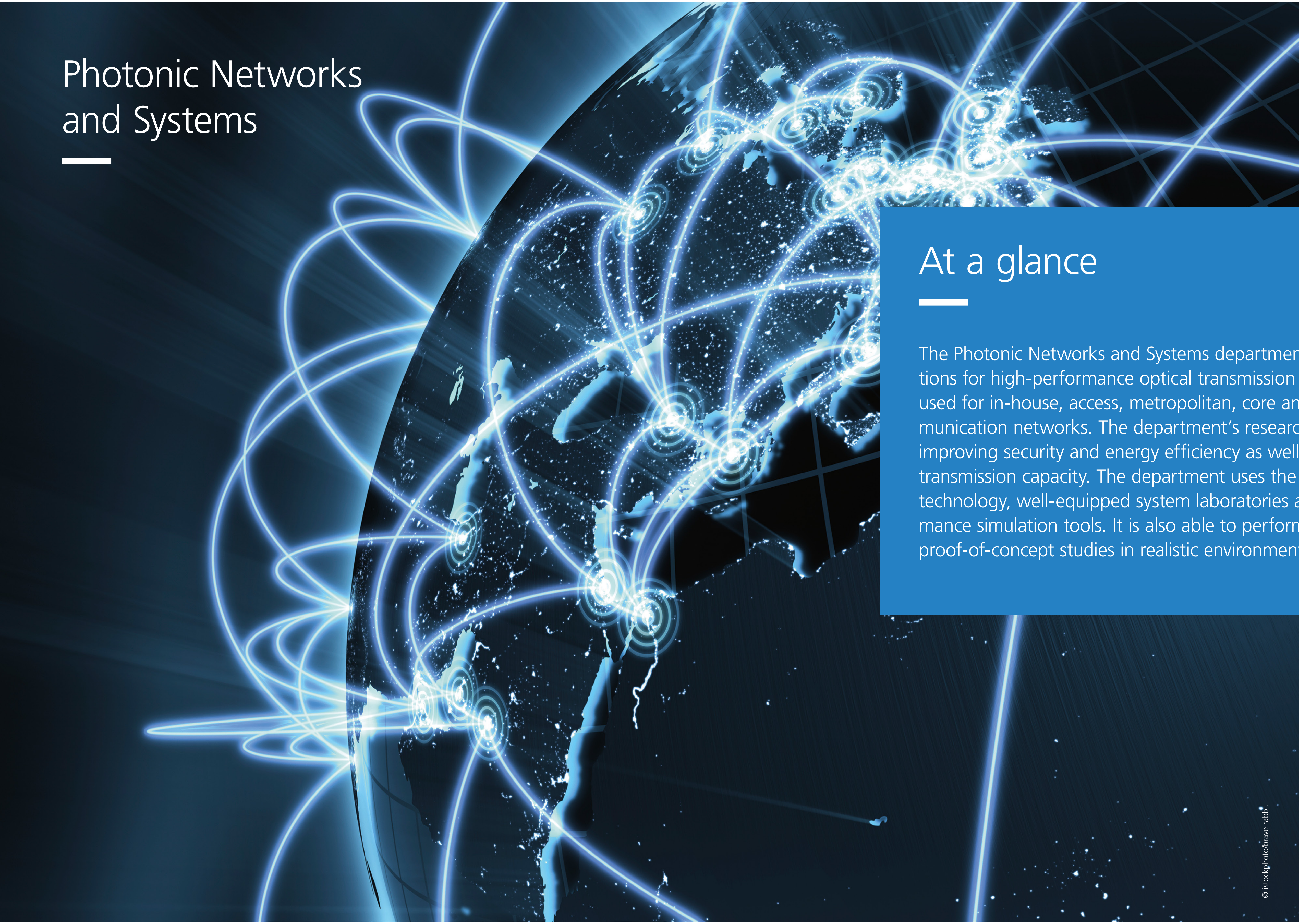
Photonic Networks and Systems



At a glance

The Photonic Networks and Systems department develops solutions for high-performance optical transmission systems to be used for in-house, access, metropolitan, core and satellite communication networks. The department's researchers focus on improving security and energy efficiency as well as increasing transmission capacity. The department uses the latest measuring technology, well-equipped system laboratories and high-performance simulation tools. It is also able to perform field tests and proof-of-concept studies in realistic environments.

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Photonic Networks and Systems

Left: laser communication terminal with optical antenna for free-space transmission; middle: THz outdoor antenna for 100 Gbit/s data transmission; right: LiFi system for operating multiple access points in order to cover larger areas

Elastic optical networks with scalable capacity and low-level latency

Network operators increasingly need to invest in their networks' flexibility and scalability. To date, overdimensioned transmission capacity in networks has been allocated in an almost rigid manner. Breaking away from this type of network dimensioning in favor of needs-based allocation of bandwidth resources in the optical layer enables existing fiber-optic infrastructure to be used more efficiently by making use of spare capacity. The focus of the research is optical transmission systems that can be configured with software, have flexible data rates and are able to make each channel's transmission capacity available with a high level of granularity in the terabit/s range. These systems can be used in both wide-area and metropolitan networks. Another challenge is finding an efficient way to integrate distributed computing and storage units – known as edge clouds – so that future 6G services can be operated with low latency. Fraunhofer HHI develops algorithms for planning and efficiently managing optical networks, which it validates in experiments.

Terabit/s satellite communication and secure quantum key distribution

Due to rising demand for bandwidth, future telecommunications satellites in geostationary orbit will be designed for terabit/s throughput rates. In light of this, Fraunhofer HHI is developing optical free-space solutions that meet the strict requirements for antenna gain (beam divergence in the 10 µrad range). The required data rates in the terabit/s range are achieved with the help of wavelength-multiplexing technology in the atmosphere's 1,550 nm transmission window. Designed on behalf of the European Space Agency, the prototypes facilitate bidirectional transmission between ground stations and satellites, even in the event of atmospheric turbulence. The open-space transmission systems that are developed are also used in the terrestrial field and for testing secure quantum key distribution systems. Fraunhofer HHI develops and tests systems based on both open space and fiber optics for quantum key exchange.

Wireless terabit/s transmission with high carrier frequencies

In addition to wireless transmission technology that already exists or is currently being researched, interest in something known as terahertz (THz) transmission has grown over recent years. THz transmission uses high carrier frequencies in the low THz range (0.1–2.0 THz), enabling data to be transmitted wirelessly over short to medium distances (1–5 km). Until recently, this transmission capacity had only been achieved by optical-fiber transmission systems. A field-ready prototype with a carrier frequency of 0.3 THz has already been successfully demonstrated, with data rates of up to 100 Gbit/s across a point-to-point free-space distance of 1 km. This development will make it possible to extend or bridge fiber-optic connections wirelessly. Other fields of application include backhaul and fronthaul scenarios in next-generation cellular networks.

Data transmission using visible light

Optical wireless data communication (also known as LiFi) is an attractive solution for fields that have special requirements when it comes to security and electromagnetic compatibility. Fraunhofer HHI has developed a form of transmission technology that enables conventional light-emitting diodes (LED) used for room lighting to transmit data wirelessly. This technology is already managing to achieve data rates in the Gbit/s range per wavelength. Current studies are examining the use of LiFi technology in industrial and medical environments. Researchers are also developing advanced communication protocols to expand network functionality in order to accommodate the high standards these applications have in the areas of reliability, latency and jitter. They are also working to advance their standardization.

Photonic Components

At a glance

Approximately every three years, the amount of data shared over the internet doubles. Through its research and development work, the Photonic Components department helps the internet keep working despite this growth. Nowadays, around every second bit on the internet comes into contact with technology from Fraunhofer HHI.

In addition to optoelectronic semiconductor components used for data transmission, the department develops integrated optical circuits. The team of Berlin-based scientists also studies related fields, such as sensors, terahertz spectroscopy and high-performance semiconductor lasers for industrial use.

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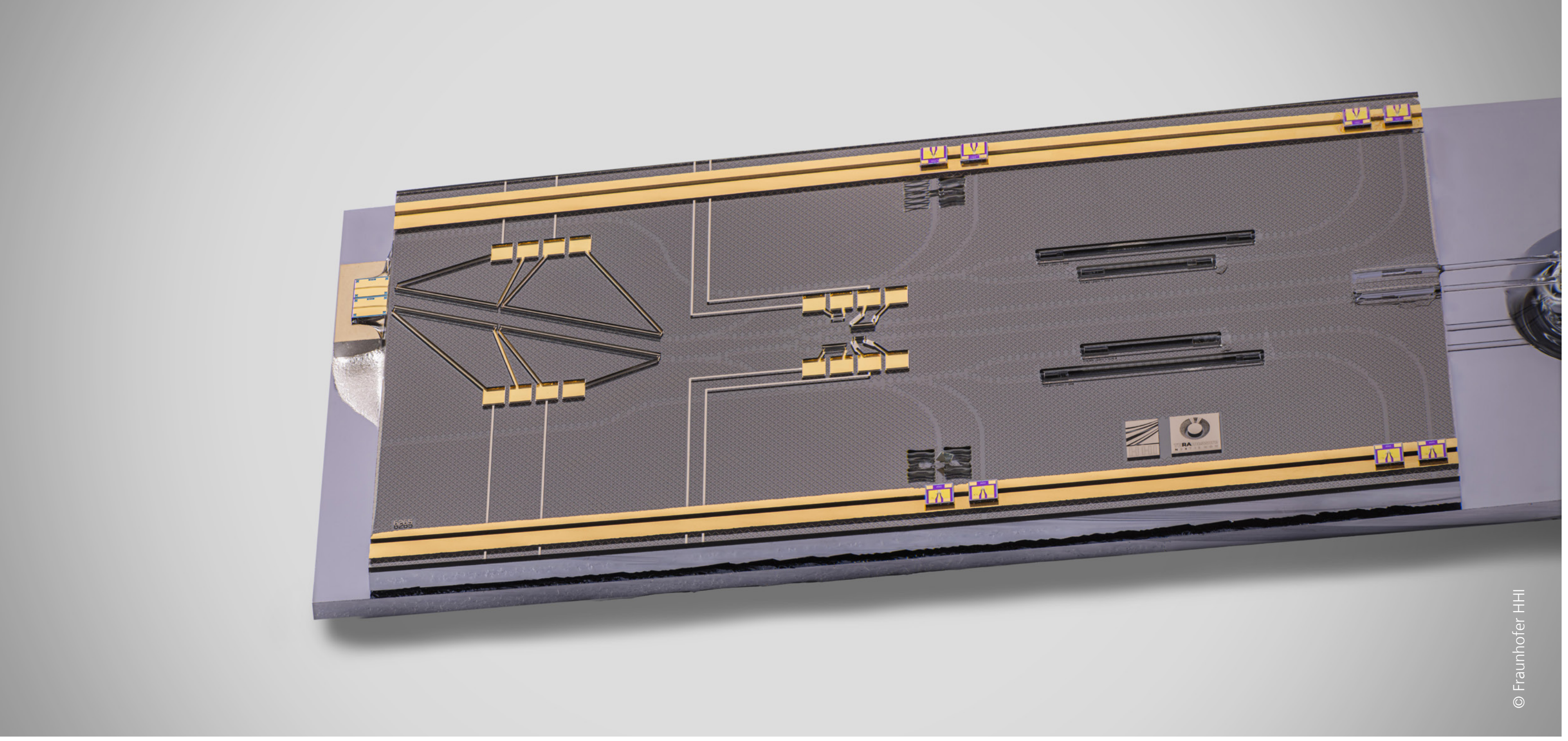

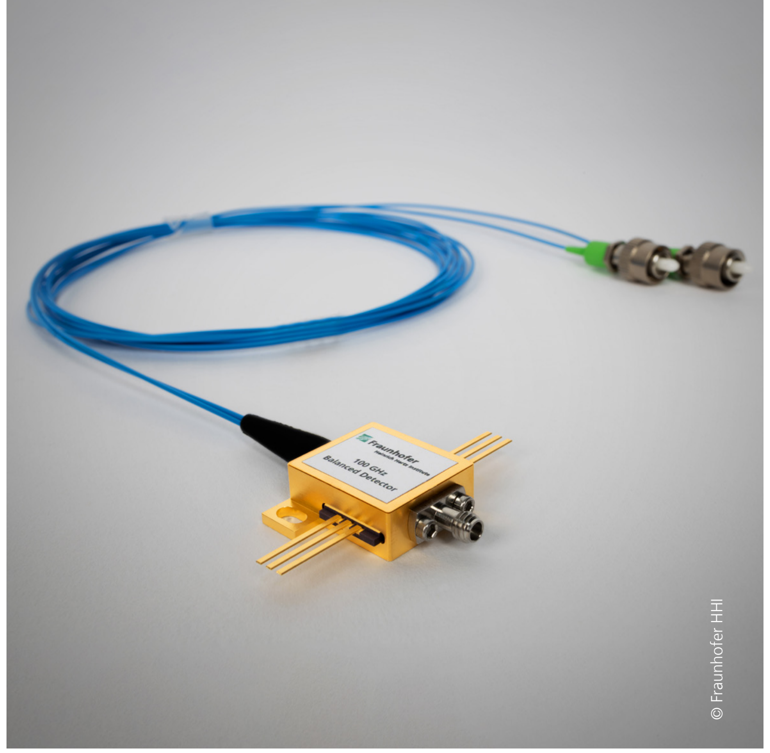

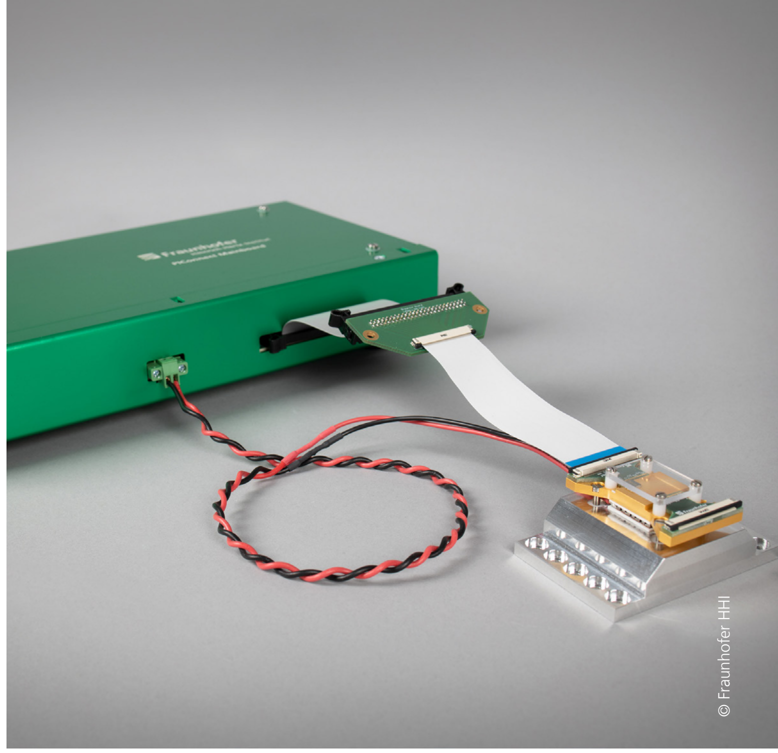

Photonic Components

Left: self-calibrated laser source (with integrated wavelength meter); middle: 100 GHz balanced photodetector module; right: PIConnect mainboard (with PIC assembly)

100 Gbaud InP-based transmitters and receivers

Approximately every three years, the volume of data on the internet doubles – demanding increasingly faster optical transmitters and receivers with wavelengths between 1,260 nm and 1,625 nm. Fraunhofer HHI is developing InP-based single-mode lasers with built-in absorption modulators for short ranges and Mach-Zehnder modulators for long ranges, along with the accompanying photodetectors. One InP wafer holds 1,000 modulators or 30,000 lasers, making InP technology extremely efficient.

In addition to high data rates, the primary aim of this research is to further reduce the amount of energy consumed per bit transmitted. Symbol rates of 100 GBaud have already been achieved in uncooled InP components, and researchers are currently working on reaching 200 GBaud. At speeds this high, co-design of InP transmission and receiver chips with their drivers or pre-amplifiers is essential.

Terahertz sensors and communication

A large number of economically important materials are transparent in the terahertz frequency range between 100 GHz and 10 THz. In contrast to ultrasonic technology, terahertz-based non-destructive testing technology allows for contact-free analysis. This is relevant in areas such as the automotive industry; for example, in monitoring the thickness of individual layers in a multi-layer paint system and their drying process. The technology can also be used to analyze reduced-weight, foam-like substances with a high air content.

Fraunhofer HHI develops terahertz transmitters, receivers and spectrometers, and markets them with our industrial partners. According to our own estimates, at least 50% of the world's terahertz spectrometers are based on Fraunhofer HHI technology. Another field of application is wireless communication at carrier frequencies above 100 GHz, along with the testing and measurement technology for these systems. Carrier frequencies on this scale achieve significantly higher data rates. Good compatibility with existing fiber-based telecommunications technology is a major advantage of the optoelectronic solutions developed at Fraunhofer HHI.

Quantum transmitters and receivers

Data security is playing an increasingly important role in our society. Quantum communication – in other words, hardware-secured quantum key distribution – enables physical security during data exchange. Here, we use existing fiber-optic infrastructure and replace only the optical transmitters and receivers with equivalent quantum components.

Fraunhofer HHI is developing quantum transmitters and receivers using established InP technology as advanced versions of components used for classic communication. For instance, Fraunhofer HHI is developing very low-noise coherent receivers and InGaAs single-photon avalanche diodes (SPAD) in the telecommunications wavelength range. At present, Fraunhofer HHI is Europe's only producer of SPAD chips.

In a second phase, these components and others will be integrated with the polymer platform to form hybrid solutions. Besides tunable, narrowband lasers in all wavelength ranges, this will enable waveguide integration of nonlinear crystals, such as $LiNbO_3$ and KTP entangled proton pair generation – a key piece of basic technology in quantum sensing and quantum computing.

Photonic integrated circuits

Fraunhofer HHI offers quick and cost-effective InP-based production services for photonic integrated circuits (PICs). As such, photonics is following in the footsteps of the CMOS success model established in the 1960s. Multi-project wafers (MPW) with client-designed PICs are launched on a quarterly basis. PIConnect – a user-friendly connection to drive PICs – makes the characterization of the PICs easier.

Sensors or quantum technologies often require wavelengths below 1,200 nm, making them inaccessible for InP. Fraunhofer HHI offers a hybrid photonic integration platform PolyBoard for this purpose. PolyBoard is transparent from near infrared to visible and – thanks to its micro-optical bench – facilitates the integration of isolators and circulators as well as nonlinear optical crystals. By combining its technology with other material platforms like SiN and LNOI, Fraunhofer HHI is able to cover almost all application fields, from medical engineering and analytics through to innovative THz-based transceiver demonstrators for wireless networks on both sides of 6G.

Fiber Optical Sensor Systems

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At a glance

Our society's transition to electrical power as its primary source of energy is leading to a steady rise in demand. To meet future demands – whether it is needed for electric mobility, green hydrogen, or heating and cooling buildings – continuous improvements to the efficiency of the technology are needed. Alongside the development of new materials and material properties, sensor technology plays an important role. The Fiber Optic Sensor Systems department is dedicated to this topic. Femtosecond laser technology is used to develop integrated optical components and systems on a glass and polymer basis, to provide novel surface functionalizations for sensors, and to process highly efficient electrode materials for hydrogen generation and storage.

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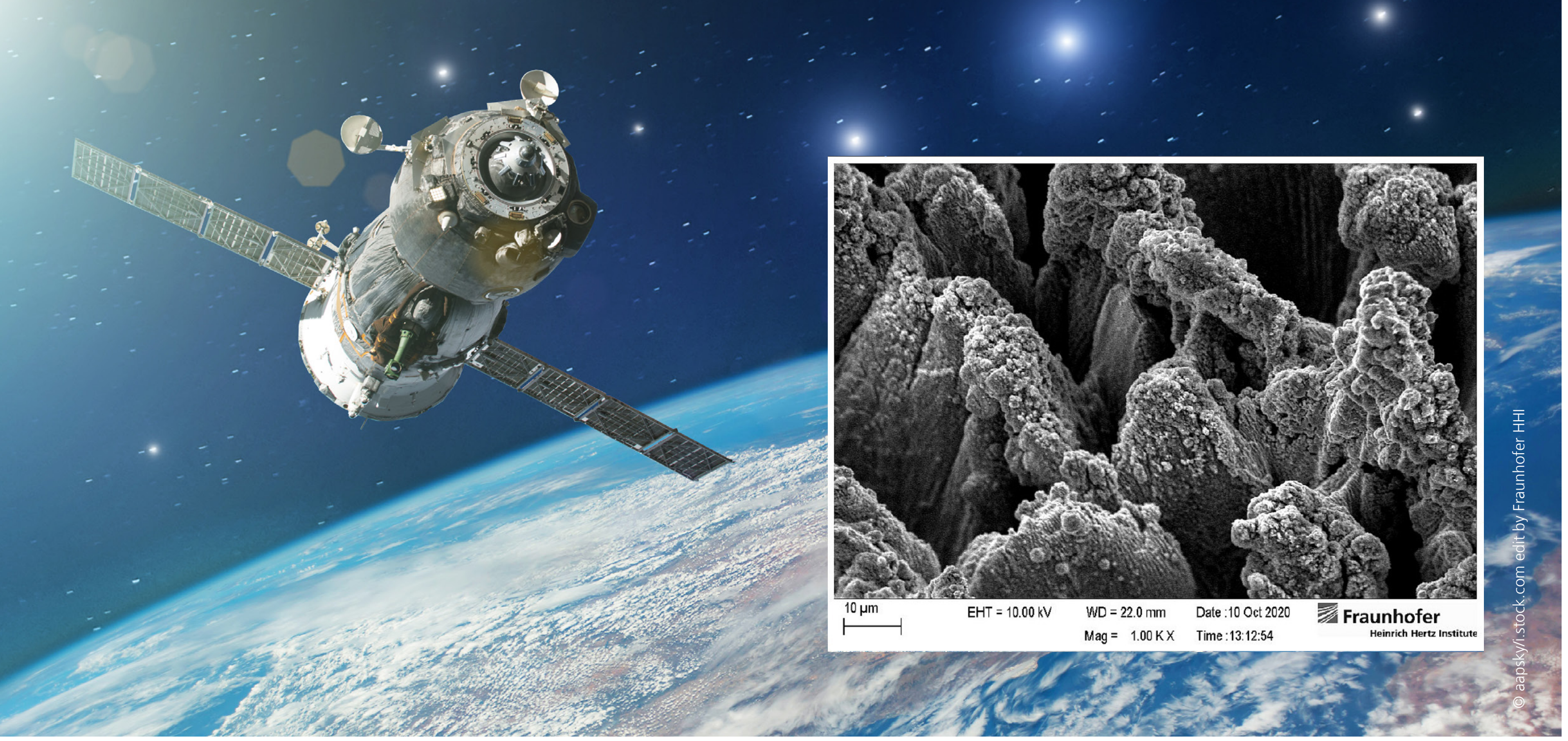
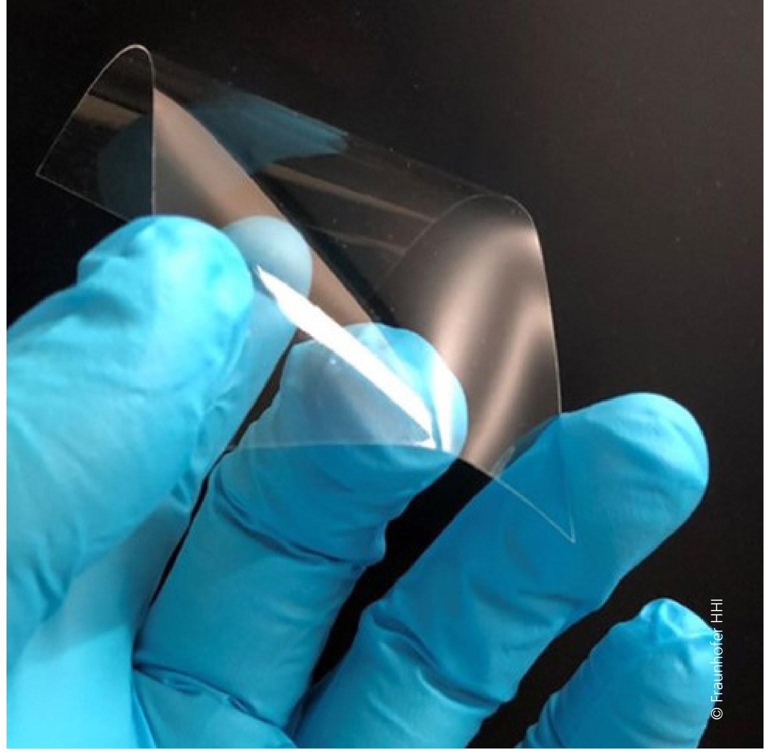
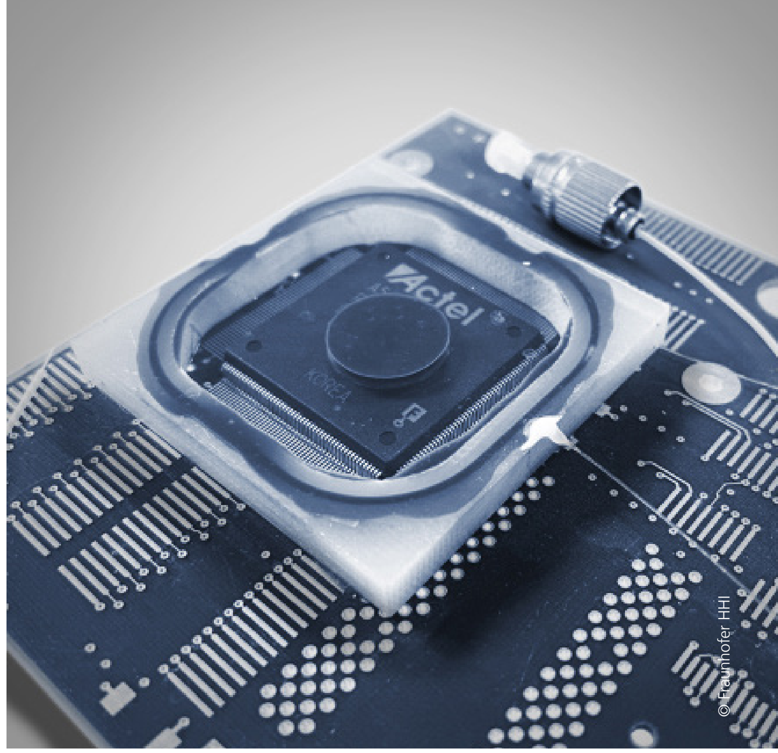






Fiber Optical Sensor Systems

Left: femtosecond laser used to process materials for temperature regulation in space travel; middle: ultrathin glass for 3D shape detection; right: optical seal

Sensors and functionalized materials for the energy transition

The interaction between femtosecond laser pulses and different materials opens up a wide field of options for adjusting specific material properties both at a surface and interior. Femtosecond laser direct-writing methods, based on multi-photon absorption processes in materials, are applied in fiber optics. These ultra-thin glass foils and polymers can produce basic elements such as optical waveguides and photonic diffractive components. For example, this integrated optics approach has been applied as a way of creating integrated optical microspectrometers. When combined with fiber-optical and planar-optical 3D shape detection, this creates novel approaches to multi-component sensors. The size of the active surfaces, wettability as well as heat emission and catalytic properties can also be adjusted by processing metal surfaces with lasers.

3D shape detection and optical seals

In collaboration with the University of Basel, the performance of the fiber-optic 3D shape sensor developed at Fraunhofer HHI has been significantly improved with the help of artificial intelligence, enabling the reconstruction of the three-dimensional shape of a 30 cm long optical fiber with an accuracy of about 2 mm compared to the reference shape. This opens up new opportunities for controlling technical and medical endoscopes. The Inherently Flexible X-Ray Imaging Detector using Single Photon Avalanche Photodiodes and Scintillating Fibres (FleX-RAY) project (Horizon 2020) is focusing on developing new, flexible X-ray imaging detectors. To achieve this, Fraunhofer HHI is developing a 3D shape sensor based on functionalized, ultra-thin glass foils used to determine the detector geometry for subsequent imaging.

In the Novel Active Optical Sealing for PRS Security Modules with Thin Glass Sensors (OTP) project co-funded by the Federal Ministry for Transport and Digital Infrastructure, the department is working with OHB Systems AG to develop a sensory security housing for permanently monitoring physical tamper attacks on mobile public regulated service security communication modules, which are used in the European satellite navigation system GALILEO. To achieve this, the vulnerable electronic components are surrounded by an optical sensory housing made out of ultra-thin glass. This glass housing incorporates an unclonable, unitary optical signature to allow for cryptographically secure initialization.

Fiber-optic hydrogen sensor technology

The H_2Security project, supported by ZIM (Central Innovation Program for SMEs), is developing fiber-optic sensors with built-in Bragg gratings to selectively detect hydrogen. The physical measurement principle is based on evanescent field spectroscopy. To increase their sensitivity and selectivity, the fibers are coated with Pd nanoparticles at the measurement points. An accuracy of rate 0.05 % is achieved in a measurement range of 0.1 % to 4 % hydrogen.

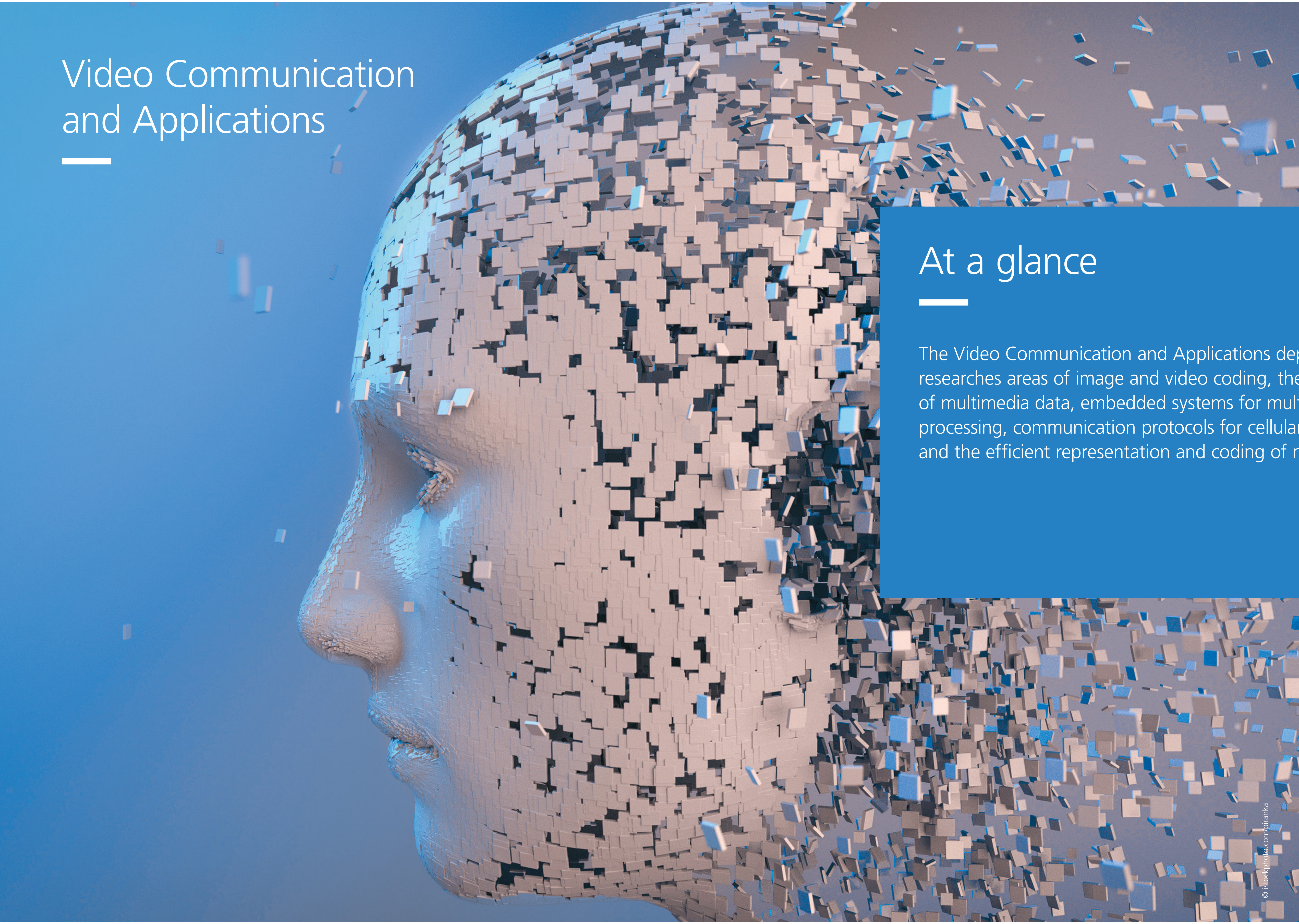
Material processing using ultrashort pulse laser technology

Ultrashort pulse laser technology is used to functionalize the surfaces of a wide range of materials, enabling their properties to be adjusted for specific purposes. The light absorption, wettability, thermal emissivity or even the size of the active surface can be changed. Material surfaces that have been optimized in this way are ideal for use as highly efficient electrodes for water electrolysis with minimized overvoltage, as heat sinks for dissipating heat in space, or as catalyst carriers for chemical reactions. This work is integrated into the Fraunhofer Cluster of Excellence – Advanced Photon Sources and the European Space Agency's (ESA) Euro Material Ageing campaign.

Battery and sensor testing center

Fraunhofer HHI's battery and sensor testing center was expanded even further in 2021, allowing it to perform thermal and electrical tests on battery systems with an energy content of up to 150 kWh under defined conditions. In addition, new and innovative concepts for advanced battery safety are developed and reviewed. Certifications are prepared in collaboration with the VDE. The center also tests transport containers, new extinguishing agents and extinguishing systems. Alongside two fire test furnaces, it is equipped with one climate container and several battery facilities with electrical power sources up to 1.2 MW. This enables battery tests in the operating range and above, which includes the complete and safe burnup of the battery with gas analysis.

Video Communication and Applications



At a glance

The Video Communication and Applications department researches areas of image and video coding, the transportation of multimedia data, embedded systems for multimedia processing, communication protocols for cellular networks, and the efficient representation and coding of neural networks.

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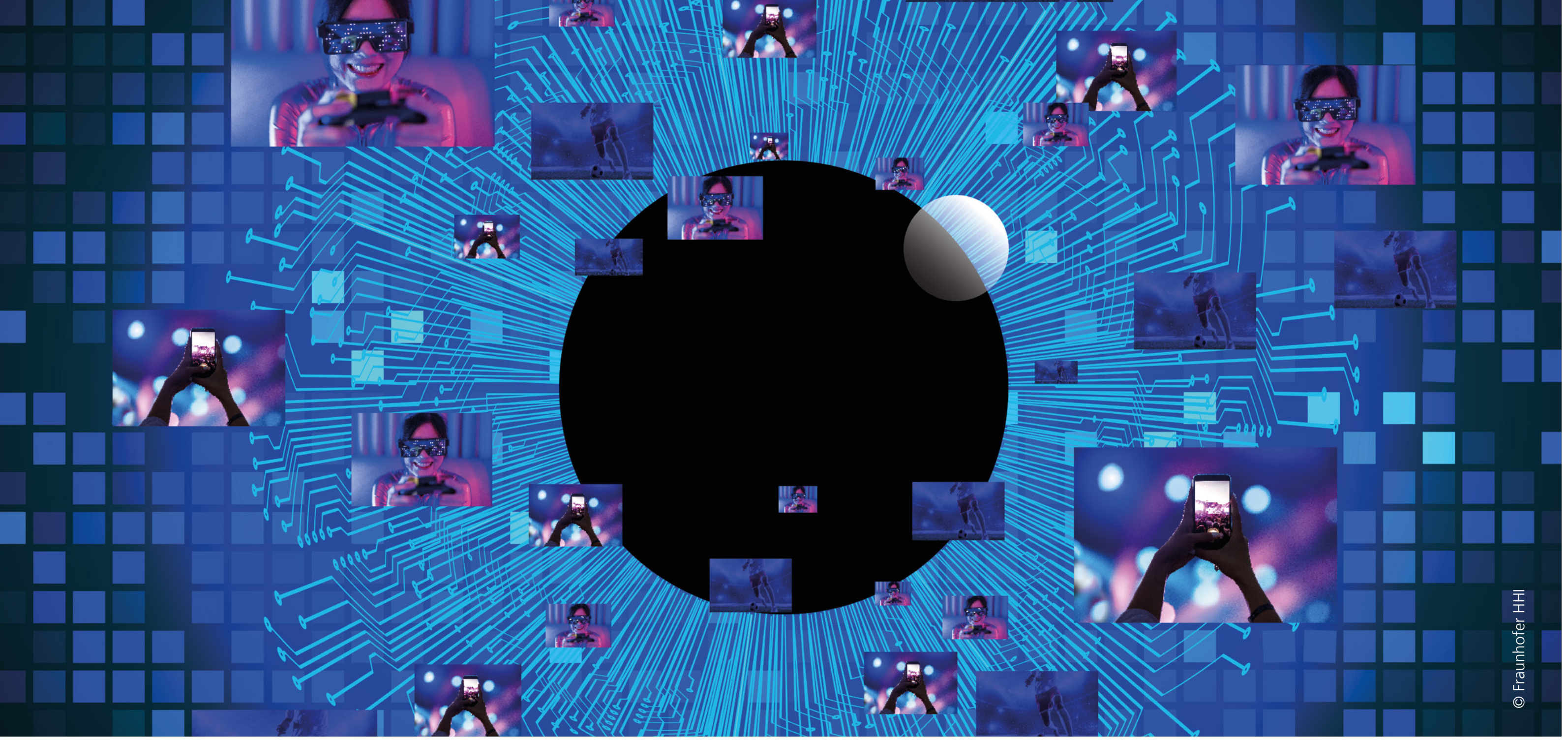

Video Communication and Applications

Top middle: playback of VVC-coded video on a tablet; top right: scene from a cloud rendering for volumetric video

Nowadays, video data account for most bits in global internet and cellular data traffic. To help overcome the challenges it presents, the Video Communication and Applications (VCA) department is constantly working to develop new video compression technology. In conjunction with industry leaders, VCA incorporates its compression technology into international standards, which facilitate interoperability when exchanging and storing multimedia content and are applied to billions of devices around the globe. With the emergence of neural networks in almost every application, the focus of compression is expanding to include the use of neural networks in video compression and the compression of neural networks themselves.

The VCA department deals with all aspects relevant to the research areas of image and video coding, the transportation of multimedia data, embedded systems for multimedia processing, communication protocols for cellular networks, and the efficient representation and coding of neural networks.

Contributions to the standardization of video codecs

The department has made a significant contribution to developing three generations of video coding standards – including the main updates they have undergone and the relevant transport and storage formats: H.264 / Advanced Video Coding (AVC), H.265 / High Efficiency Video Coding (HEVC) and H.266 / Versatile Video Coding (VVC). Billions of devices around the world use the AVC and HEVC video compression standards. Half of all bits on the Internet are generated and processed by compression technology developed by VCA.

VCA played a major role in developing the recent H.266/VVC standard, which reduces the bit rate by 50% compared to the current state of the art (the HEVC standard) while still maintaining the same image quality for viewers. The first version of the VVC standard was finalized in July 2020 and – in addition to advanced versions of already familiar technology – also contains radically new compression methods developed using techniques such as machine learning. Furthermore, the first version of VVC is already equipped with special coding tools and system functions for a wide range of applications, such as adaptive streaming with varying resolutions, 360° immersive video, streaming with extremely low latency, game applications and screen content sharing.

Contributions to the implementation of video codecs

The open-source Fraunhofer Versatile Video Encoder (VVenC) software developed by the VCA department was awarded first place in the Best Open Source Project Awards during the IEEE International Conference on Multimedia and Expo (ICME) 2021. VVenC is a quick and efficient encoder implementation of the H.266/VVC standard.

VVenC makes it possible to use the significant reduction in the data rate, as offered by the new VVC standard, in countless multimedia applications within today's connected society. Examples include streaming, virtual reality and augmented reality. With this solution, the software can also be flexibly configured according to the various requirements for quality and encoder runtime.

Contributions to the standardization of multimedia systems

After two years of standardization work, the Moving Picture Experts Group (MPEG) completed its work on scene description through an enhanced version of the Graphics Language Transmission Format (glTF). The glTF is an industry standard developed by the Khronos Group for describing three-dimensional models and scenes. The new update enables volumetric video and audio to be integrated into an immersive scene for the first time. Fraunhofer HHI played an important role in the research and development of the new standard.

MPEG's upgrades to glTF include mesh linking technology, which was developed by Fraunhofer HHI. This enables the high level of realism in volumetric videos to be combined with animation capabilities in computer graphics models. Photorealistic virtual humans can now be integrated into mixed-reality scenes to facilitate interaction with users. For example, a photorealistic avatar can now actively maintain eye contact with a user, something that was previously only possible with computer graphics models – not with much more realistic-looking but also more complex volumetric video content.

Vision and Imaging Technologies

At a glance

The Vision and Imaging Technology department researches cutting-edge technology for the entire visual data processing chain, from the capturing and analysis of visual content and digital representation modeling through to realistic visualization and human-machine interaction. Its primary focus is on sophisticated AI technology in the fields of computer vision, visual computing, 3D modeling and simulation, cognitive systems, and immersive media. With our technology, we offer solutions for a wide range of applications in industry, medical engineering, agriculture, construction, safety and security as well as for virtual, augmented and extended reality.

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Vision and Imaging Technologies

Left: intraoperative assistance systems; middle: AR support in production and assembly; right: detection of attacks on authentication systems

The past few years have seen a huge rise in the roles of understanding and interpreting the visual world by computers, digital representations of the real world in authentic digital models, and interaction with digital content in immersive environments. The technologies developed by researchers at Fraunhofer HHI detect, track and analyze objects and people, and their movements and textures, and then reconstruct realistic digital representations. Modern processes used to model and animate digital models enable visual content to be synthesized for media applications, for simulations of industrial processes or for training of highly complex AI solutions. Our researchers also develop technologies that enable humans and machines to work together effectively thanks to new modes of interaction, intelligent environments and visualization techniques.

Technology for industry, construction, agriculture and medicine

State-of-the-art computer vision and AI solutions can help to make workflows in industry, construction and agriculture more efficient and secure. Elements such as virtual representations of real-life objects (digital twins) are essential parts of modern automation and engineering processes. The technologies range from solutions for visual inspections using cutting-edge AI solutions to image-based methods for high-precision, reliable dimensioning, process monitoring, analysis and 3D scanning of complex components, buildings and spaces, all the way through to augmented reality assistance and human-machine interaction to support workflows in production, construction and agriculture. Even workflows in the medical sector can be supported by cutting-edge computer vision and AR-based technology, such as intraoperative assistance systems. For instance, real time-capable 3D measurement using endoscopes or operating microscopes allow implants to be customized. Work on hyperspectral-based tissue analysis and video-based monitoring of perfusion and vital parameters allows additional information to be made available intraoperatively in real time. Contact-free human-machine interaction and user-adaptive data and image visualization contribute to the intuitive design, while still ensuring compliance with clinical hygiene standards. These methods make medical interventions safer, simplify workflows and improve medical working environments for the long term.

Technology for increased immersivity in XR

New media and communication formats – such as extended, virtual and augmented reality (XR, VR and AR) – call for innovative solutions. Here, the challenge lies in making virtual content and environments as realistic as possible in order to achieve the highest possible level of immersivity. The realistic modeling of virtual humans who can interact with users is particularly essential for countless immersive applications. Using volumetric video technology as a basis, Fraunhofer HHI has developed innovative hybrid representations of virtual humans with the help of modern AI methods. As a result, a person's individual movement patterns and facial expressions can be learned in relation to speech, for example, and new animations can be accurately synthesized. Modern neural visualization methods help to ensure a realistic appearance. Our researchers work closely with neuroscientists to research how virtual humans are perceived. Furthermore, the department develops new media formats for immersive audiovisual representations in a range of applications. Its development work here focuses on immersive video and audio technology, recording and playback processes, and low-latency transmission processes. The goal is to achieve the highest possible level of immersion, be it for virtual participation in life events, virtual training (e.g., for medical staff) or the simulation of infrastructure measures in urban development.

Secure authentication with AI

The Vision and Imaging Technologies department develops reliable algorithms for detecting attacks on image-based and video-based authentication systems using fake identities. In particular, we study reliable AI processes for detecting what are known as morphing attacks (manipulated reference images), presentation attacks (the simulation of fake identities through the presentation of images, screens or models) and deep fakes (synthetic images or videos that use AI methods). We have focused particularly on the reliability and interpretability of AI methods for security-related applications.

Wireless Communications and Networks

At a glance

The Wireless Communications and Networks department researches the area of wireless data exchange. Working closely with a number of companies and organizations, our researchers contribute to theory, concept development, technical feasibility studies and standardization in the area of wireless systems. Scientific studies, simulations and assessments at link and system level, field measurements, and the development of hardware prototypes complete the department’s range of services.

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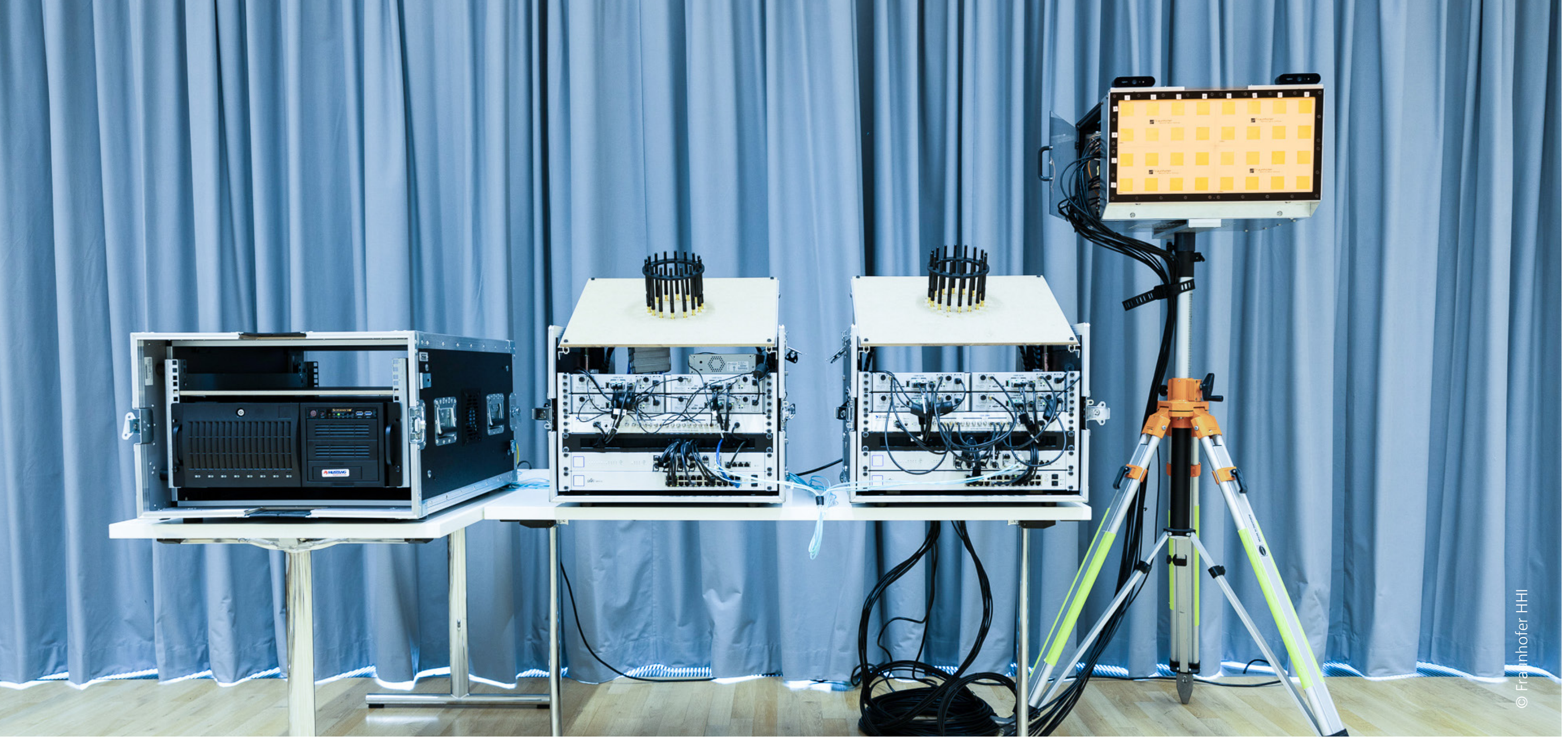

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Wireless Communications and Networks

Left: research on virtualized 5G and 6G wireless access networks; middle: ongoing vital data transmission and processing across 5G campus networks; right: reliable drone communication outside the line of sight (Wingcopter during vertical take-off in Malawi)

Research and standardization for 5G and 6G

The roll-out of fifth-generation (5G) public cellular networks is well underway all over the world. As this is taking place, research and standardization for 5G are still progressing. Additional functionalities and protocols are being developed and standardized by the 3rd Generation Partnership Project (3GPP) with the aim of supporting applications for vertical industries. Within this process, the focus is shifting increasingly toward local and customer-specific 5G cellular networks — known as campus networks.
The creation and operation of campus networks, including the various operator models, have yet to be fully researched. Particular industry-specific requirements for vertical applications have to be taken into account in this context, along with the basic conditions they need, and this presents some major challenges. The goal is to develop bespoke solutions that are appropriate for the specific needs and basic conditions of campus networks. This will generate unique opportunities for German start-ups, the SME sector and innovations within the 5G environment. Using Open radio access network (RAN) as a basis, the Wireless Communications and Networks department develops 5G solutions for open campus networks, helping to creating new value chains within these networks.

In addition to its work on open 5G campus networks, the department has started researching the sixth generation of cellular networks (6G). The main challenges for researchers lie in the radical rise in data rates that apply in planned 6G applications (such as mixed realities). There are also new challenges resulting from the integration of sensor services (network-as-a-sensor solutions). Artificial intelligence will be one of the most important sources of innovation for 6G. The aim in applying it will be to promote the convergence of information and communication technology. Ultimately, 6G will integrate non-terrestrial communication and networks (satellite and drone communication, and so on) in an effort to achieve an extremely high degree of network coverage around the world (in rural and sparsely populated areas, for example).

Ongoing vital data transmission and processing across 5G campus networks

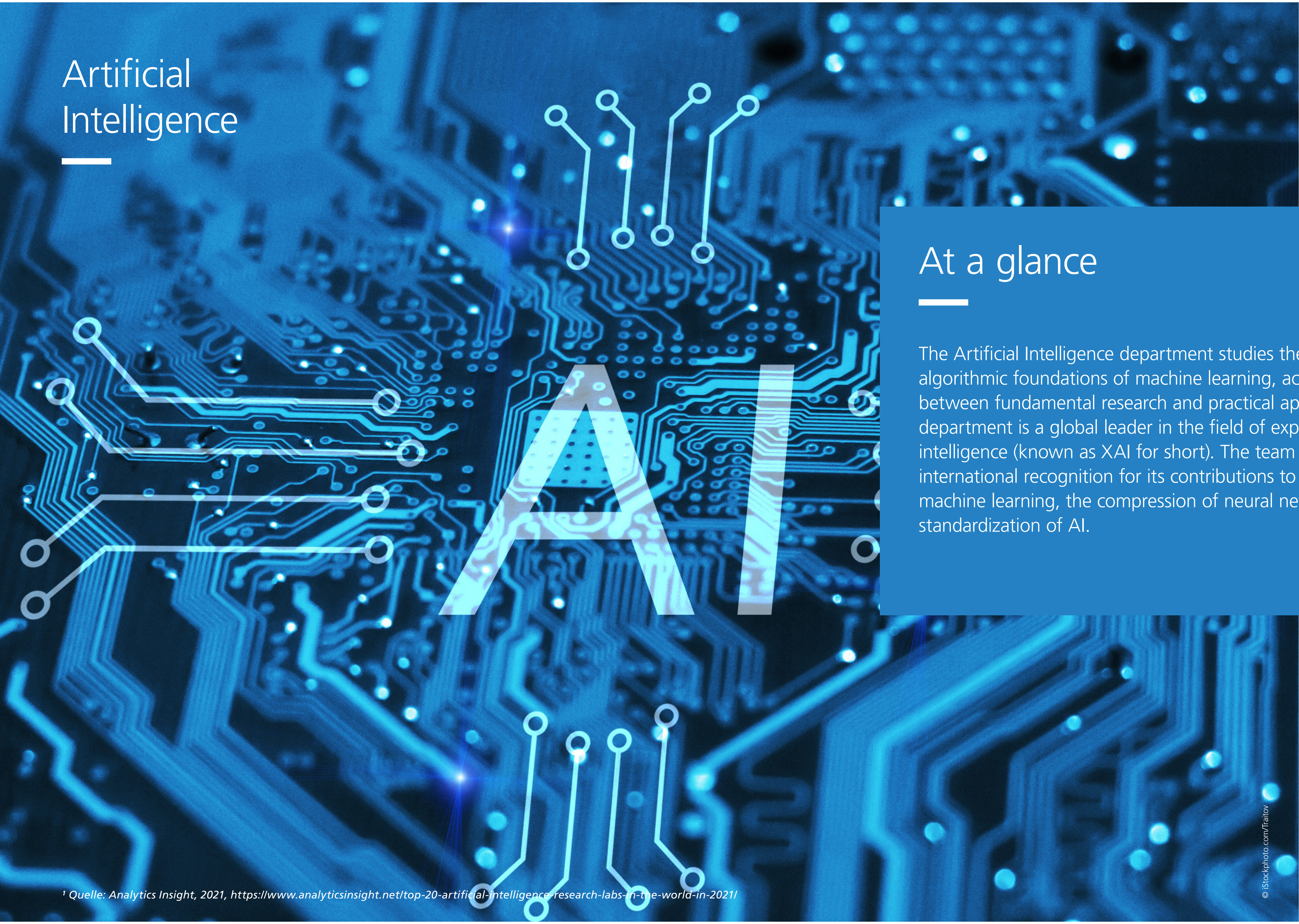
Patients in the final stages of chronic heart failure often require permanent mechanical circulatory support (in the form of left ventricular assist devices or LVAD) and/or a heart transplant. However, their underlying cardiological disease, the possible complications arising from the implant and comorbidities present major challenges to their post-operative long-term care. The 5GMedCamp project’s goal is to improve telehealthcare for LVAD patients using 5G technology and methods involving artificial intelligence, creating a technological basis for close real-time monitoring. The aim is for the results on the use of 5G campus networks in the medical sector to form the foundation for enabling multi-dimensional technological opportunities involving connectivity, digitalization and AI to be used in patient telehealthcare.

Reliable drone communication outside the line of sight

In the future, drones will increasingly be used to operate outside of a controller’s line of sight. Due to their limited range, conventional remote control systems are not suitable for this type of application. If cellular networks are experiencing high loads or there is a lack of network coverage, simple cellular systems are unable to guarantee reliable communication. In order to meet the high safety and security requirements of the aviation industry, it is essential that intervention in flight plans is possible at all times. This means that safety-critical and security-critical information must be transmissible without any interruptions. To achieve this, several types of technology are combined to form a complete system with a high degree of reliability. State-of-the-art 5G technology – which is likely to be joined by 6G in future – involving multiple-input and multiple-output antenna systems (MIMO) provides the basis for this.

Research and development

- Fifth-generation and sixth-generation cellular networks (5G/6G)
- Campus networks
- Sub-THz communication for mobile access
- Deep integrated machine learning
- V2X communication
- Drone communication
- Network as a sensor
- Intelligent reflective surfaces
- PHY-layer security
- Semantically supported communication
- Software-defined radio (SDR)
- Autonomous convergent networks



Artificial Intelligence

*The AI department was named one of the **Top 20 Artificial Intelligence Research Labs in the World in 2021**[1] and has received awards such as the Pattern Recognition Medal, several ESI Highly Cited publications and the Hugo Geiger Prize.*

At a glance

The Artificial Intelligence department studies the theoretical and algorithmic foundations of machine learning, acting as a bridge between fundamental research and practical applications. The department is a global leader in the field of explainable artificial intelligence (known as XAI for short). The team has also gained international recognition for its contributions to distributed machine learning, the compression of neural networks and the standardization of AI.

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[1] Quelle: Analytics Insight, 2021, https://www.analyticsinsight.net/top-20-artificial-intelligence-research-labs-in-the-world-in-2021/


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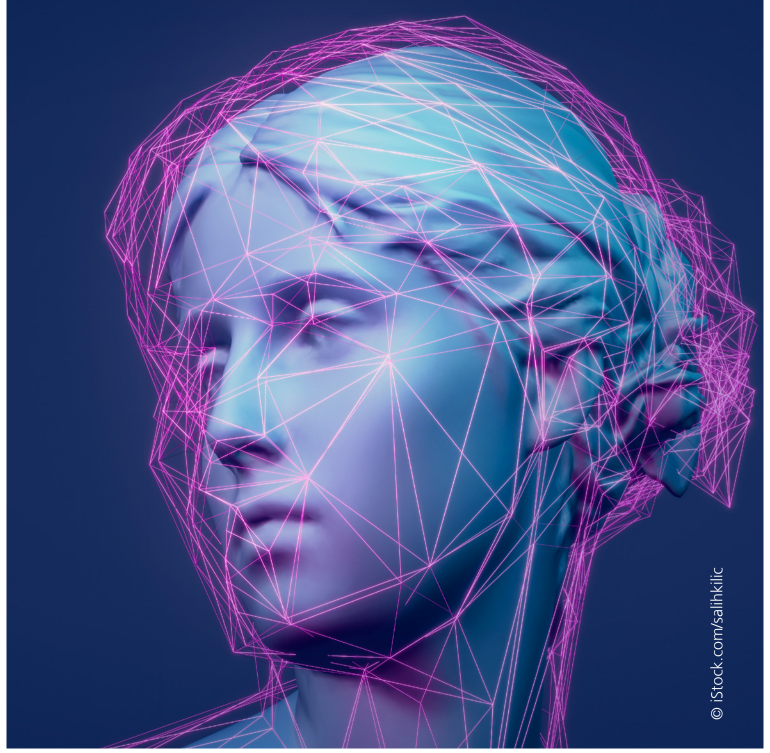
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Artificial Intelligence

XAI: the bridge between humans and AI

Through its work on explainable AI, the department has created an innovative communications interface between AI and the user. Layer-wise Relevance Propagation (LRP), a process designed by the department in conjunction with the Technical University of Berlin, enables users to track AI decisions at an in-depth level. LRP is one of the world's most frequently used methods in the field of XAI. The method's potential stretches far beyond simply explaining decisions, however.

In its work, the team has demonstrated how LRP can be used to systematically debug and improve the AI model. Explanations also provide a wealth of opportunities for integrating a priori knowledge and carefully controlling aspects of the model during training. Research into the potential of XAI goes much further than just explaining and the systematic improvement and specific adjustment of explanations to respond to practical issues are also areas of focus within the team's research. Various pieces of XAI technology created by Fraunhofer HHI are available to the research community as open-source software to help advance the field of explainable AI with a leading, sustainable approach.

Viewing the AI lifecycle as a whole

To enable AI systems to be used in safety-critical applications such as autonomous driving or clinical diagnostic systems, attributes such as security, robustness, explainability and reliability are of key importance. In order to safeguard these, the entire AI lifecycle – from data acquisition and labeling to AI model design and training, all the way through to systematic validation and monitoring of the model – must be taken into account. Through its work, the department contributes to all phases of the AI lifecycle and maintains a holistic overview of the development process. By participating in various national and international standardization initiatives in the field of AI, such as the ITU/WHO focus group AI for Health or the Germany Institute for Standardization (DIN) roadmap, the team is helping to establish novel testing and certification standards for secure, robust, explainable and reliable AI.

AI research with a practical impact

The department develops AI methods and models that offer practical benefits. Challenges such as limited and distributed training data, a high degree of multimodality or limited processing resources do not impede the model training process. Our techniques for explaining AI decisions, generating synthetic training data or testing and debugging fully trained models are used at central points in a range of cooperation projects. These include projects in the medical sector for analyzing epidemiological data to assess risk factors, taking full-body images to identify abnormal changes to the skin or taking 3D CT images of the heart to identify calcification. The technology is also used to evaluate more complex sensor and weather data as a means of predicting air quality, and to analyze mobility data when developing early-warning systems for natural disasters.

Federated learning: distributed, private, efficient

Another area of focus in the department's research is the development of improved methods for federated learning, which enables us to efficiently train AI models in distributed data while protecting privacy. In this context, the team is particularly interested in developing improved compression methods for neural networks and federated learning, and in examining the interaction between learning, compression and communication. The compression methods developed by the AI and VCA departments lead to huge savings in neural network sizes and communication in federated learning. They form the basis for the first international Neural Network Coding Standard (ISO/IEC 15938-17). New approaches for indirect knowledge exchange (known as federated distillation), model personalization and verifiable privacy guarantees are also studied by the department.

A member of the Berlin AI landscape

The department's team is closely integrated into Berlin's AI landscape in a range of ways — for example, as a member of BIFOLD (Berlin Institute for the Foundations of Learning and Data), as part of the DFG research group DeSBi[2] or through a chair at the Technical University of Berlin. Thanks to its participation in the Konrad Zuse Schools of Excellence in AI (ELIZA) and various graduate schools, the department is actively involved in training talented AI specialists of the future.

[2] Fusing Deep Learning and Statistics towards Understanding Structured Biomedical Data

"

Politics. Science. Research.

We create a network of people from across the globe."

Dr.-Ing. Ralf Schäfer
Director of the Video Division, Fraunhofer HHI

Showrooms

Fraunhofer HHI's showrooms are where the technologies developed at the institute are displayed for people to experience – which in turn gives them an important role in transferring technologies to industry. The showrooms also serve as communication platforms for dialogue with decision-makers from the worlds of industry, politics and society.

CINIQ Center – Forum Digital Technologies

Located in Berlin, the CINIQ Center is a location for technology and information transfer that operates at the intersection of innovation, science and industry.

Since 2019, the Forum Digital Technologies has been using the CINIQ premises to showcase selected research projects and innovations in the field of digital technologies. There, events and guided tours provide visitors with an insight into the vital discourse that takes place on the subject of digitalization, encouraging dialogue between groups of experts.

The Forum Digital Technologies receives financial support from the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

TiME Lab – Tomorrow's Immersive Media Experience Laboratory

The TiME Lab showroom was created as a research, collaboration and presentation platform for immersive media. It is equipped with high-resolution 180° video projection, plus a 3D sound system based on wave fields. TiME Lab is home to numerous systems and fields of application that have undergone systematic research and implementation over the years. Since its foundation, it has carved out a position for itself as a platform for realistic audiovisual presentations of city planning concepts and measures for infrastructure building and noise protection.

3IT – Innovation Center for Immersive Imaging Technologies

The showroom encompasses a virtual network plus an exhibition space and events venue in the heart of Berlin. In the 3IT center, new technologies for industrial, medical and cultural applications are developed, tested and presented to a range of target groups. Its focus is on 3D, VR/AR/XR, volumetric video, UHD and HDR technologies.

Collaborations and Fraunhofer groups

Shaping the digital society of the future – together

Researchers at Fraunhofer HHI collaborate with a range of experts from across the globe to create advancements in technology and put them into practice. Fraunhofer HHI also works with numerous local partners with the aim of giving innovations greater visibility and strengthening the Berlin/Brandenburg region's status as a scientific hub.

5G BERLIN e. V.

The **5G BERLIN** cluster connects the traditional telecommunications industry with new 5G stakeholders and the Berlin start-up scene. It operates its own dedicated 5G test field in the heart of Berlin and offers members in the vicinity the opportunity to test out new 5G technologies under real-life conditions. As an innovation cluster, its focus is on promoting 5G applications that use augmented reality (AR) and virtual reality (VR), and it also encourages advancements in areas such as intelligent mobility, intelligent supply networks, security applications and Industry 4.0.

Optec-Berlin-Brandenburg e. V. (OpTecBB)

OpTecBB is an association of 115 companies and scientific facilities that are active in the fields of optical technologies and microsystems engineering. Its focus is on photonics and quantum technologies for communications, sensors, optical analytics, light technology, biophotonics, ophthalmic optics, laser technology and microsystems engineering. Prof. Martin Schell is chairman of the OptecBB managing board.

European Photonics Industry Consortium (EPIC)

EPIC is the leading industry association in the European photonics sector, providing a networking hub for more than 800 industrial companies, research institutions, SMEs and start-ups. As an advocacy group, it focuses on the sustainable development of technologies and on promoting a vibrant photonics ecosystem. Prof. Martin Schell was a member of the EPIC's Board of Directors from 2015 to 2021.

Photonics21

Technology platform **Photonics21** provides representation for the European photonics industry and research organizations working in the field. In collaboration with the European Commission, it has developed a joint research strategy as part of a Horizon Europe public-private partnership (PPP) with the aim of stimulating growth and employment opportunities in Europe. Since 2014, Prof. Martin Schell has been HHI's representative on the platform's Board of Stakeholders.

Berlin Institute for the Foundations of Learning and Data (BIFOLD)

BIFOLD promotes fundamental research in big data management and machine learning, plus the areas in which they intersect. Alongside its partners, the institute is focused on developing Berlin's status as a standout location for AI research. To achieve this, BIFOLD provides regular opportunities for discussion between AI researchers from various institutions and sets up several programs designed to support up-and-coming talent.

Video Coding Experts Group & Moving Picture Experts Group (MPEG)

Fraunhofer HHI has made a significant contribution to developing three generations of video coding standards, the main updates they have undergone and their associated transport and storage formats: **H.264/Advanced Video Coding (AVC), H.265/High Efficiency Video Coding (HEVC)** and **H.266/Versatile Video Coding (VVC)**. Fraunhofer HHI technologies also play a key role in the standard governing the compression of neural networks for multimedia applications (the **NNR standard**) and the latest upgrade to the **Graphics Language Transmission Format (glTF)**.

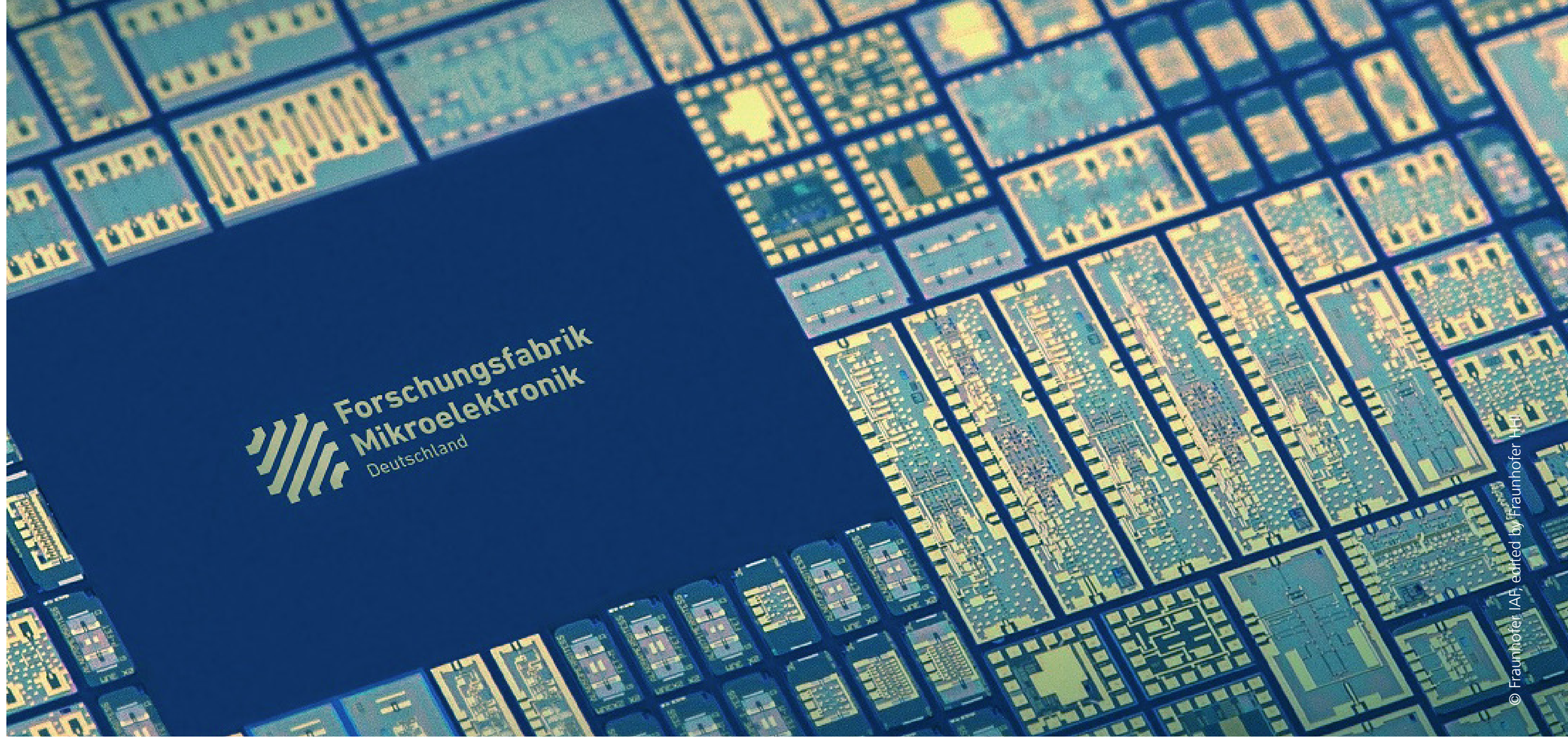
Member of Fraunhofer groups:

- Microelectronics
- ICT Group (associated institute)
- Light & Surfaces (associated institute)

Member of Fraunhofer alliances:

- Ambient Assisted Living AAL
- Cultural Heritage Research
- Battery
- Big Data and Artificial Intelligence
- Digital Media
- Aviation & Space
- Vision
- Digital Networking High-Performance Center

Research Fab Microelectronics Germany



Key partner to industry, science, politics and society

2,000 researchers in the FMD

Since 2017, Fraunhofer HHI has been working with ten other institutes in the Fraunhofer Group for Microelectronics, plus the FBH and IHP institutes within the Leibniz Association, to form the cross-location Research Fab Microelectronics Germany (or FMD for short).

For the first time, this collaboration is providing an opportunity for 13 research units and institutions from Fraunhofer and Leibniz to pool their expertise under a shared virtual banner. In doing so, they are reaching new heights in the standards achieved in researching and developing microsystems and nanosystems. Home to more than 2,000 researchers, the FMD is the world's largest research and development (R&D) collaboration of its kind. The unique diversity of specialities and infrastructure that the FMD delivers through its institutes is helping to ensure that Germany and Europe reinforce their leading position in research and development.

Transitioning to normal operation

At the end of 2020, the FMD was still in its development phase. The extensive investments in modernizing the institutes, provided by the German Federal Ministry of Education and Research (BMBF), came to the end of their terms in late 2020/early 2021 with the exception of a few delays caused by the COVID-19 pandemic.

At the start of 2021, the FMD began amalgamating the central offices of the Fraunhofer Group for Microelectronics and the Research Fab Microelectronics Germany on a permanent basis, with Dr. Stephan Guttowski taking on the role of managing director of the new joint central office. An online conference titled "Impulsgeber FMD: Angebot & Potenzial – Köpfe & Know-how" (FMD catalysts: opportunities and potential – experts and expertise) was held on April 22, 2021 to mark the new arrangement. The model, which represents interdisciplinary and interorganizational collaboration within the German research landscape, is already beginning to bear its first fruits and it is hoped that it will set a precedent within Europe in the future.

Networking and collaboration for technological sovereignty

Since its launch, the FMD has established itself as a prime example of a modern approach that assembles expertise from different R&D institutions alongside a shared strategy and a combined range of services on offer to industry players. Through collaborative work that crosses the boundaries of locations, technologies and areas of expertise, the FMD is able to maintain and develop technological sovereignty along the entire value chain.

The team at the Berlin central office represents the FMD institutes and provides a central point of contact for handling any questions about microelectronics and nanoelectronics research and development in Germany and Europe.

A range of collaboration opportunities

In addition to the services it offers its industry customers, the FMD provides a range of collaboration opportunities for its partners working in science and education. The aim of these is to approach research-related issues from a shared standpoint – by working together in research projects and operating joint labs, for example. A highlight of these collaboration opportunities is the ability to trial concepts and solutions stemming from fundamental research at the facilities provided by the FMD institutes, making it possible to gain a better understanding of how well suited the concepts and solutions are to environments of a more applied nature.

Trustworthy, sustainable microelectronic systems for enhanced innovative strength

A society that is built for the future will be reliant on electronic components in every important application domain, whether that involves critical infrastructures, Industry 4.0, the automotive sector or medical devices. People need to be able to rely on these components in order to use them for building trustworthy products, systems and infrastructures.

Working in large-scale projects such as TRAICT (TrustedResourceAware ICT) and Velektronik, the institutes in the FMD develop the cross-technology areas of expertise that are needed to rise to this challenge. The TRAICT project, for example, saw eight FMD institutes working with a further ten Fraunhofer institutes until the end of 2021 on developing basic conditions for ensuring that information and communication technology is reliable and compliant with data protection requirements, and at the same time is able to be used autonomously and securely.

Velektronik, a platform for trustworthy electronics, was launched in March 2021 as a way of providing a clearer view of the value chain as a whole and creating consistent concepts for trustworthy electronics in Germany and Europe. The platform involves 12 partners in total: 11 FMD institutes plus the edacentrum. The aim is for the project to provide a venue for developing and putting into practice standards and processes on the basis of a national and European chip security architecture.

Central office

Research Fab Microelectronics Germany
c/o Fraunhofer Group for Microelectronics

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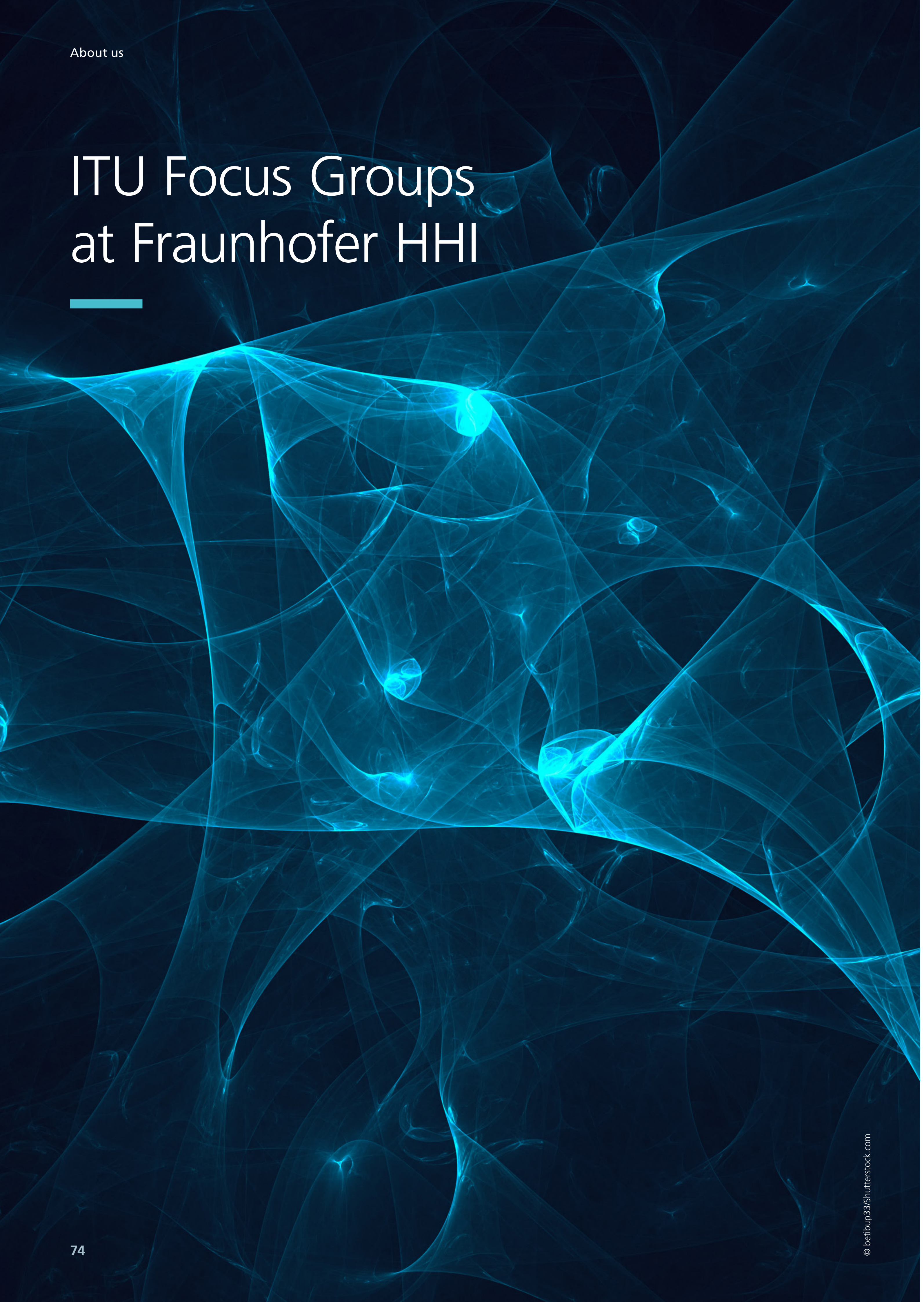
10178 Berlin

ITU Focus Groups at Fraunhofer HHI



Through its collaborative work, Fraunhofer HHI makes a major contribution to developing and standardizing artificial intelligence (AI) in the fields of medicine, disaster risk reduction and agriculture.

540
experts work together at FG-AI4H

Fraunhofer HHI coordinates three focus groups within the International Telecommunication Union (ITU). Within these groups, the ITU brings together international experts with the aim of developing strategies for using new communication technologies in a range of industries and other areas of life.

ITU/WHO Focus Group on Artificial Intelligence for Health (FG-AI4H)

FG-AI4H focuses on establishing principles for applying artificial intelligence globally in the healthcare arena. With this aim in mind, its team is developing a standardized framework for evaluating AI-based methods to be used in decisions relating to health, diagnostics, triage and treatment. During the COVID pandemic, the focus group established an ad-hoc group concerned with using digital technologies as a means of supporting the pandemic response. The focus group is coordinated by Prof Thomas Wiegand and was established in 2018 in coordination with the World Health Organization (WHO).

ITU/WMO/UNEP Focus Group on AI for Natural Disaster Management (FG-AI4NDM)

FG-AI4NDM unites experts with the aim of researching how AI-based technologies can be used to improve resilience to natural disasters. Its researchers focus on best practices when using AI to detect, forecast, or communicate (e.g., through early warning systems) natural disasters.

The focus group is coordinated by Dr. Monique Kuglitsch and is a partnership between the ITU, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). It was established in 2021.

ITU/FAO Focus Group on Artificial Intelligence (AI) and Internet of Things (IoT) for Digital Agriculture (FG-AI4A)

FG-AI4A investigates the use of artificial intelligence and the Internet of Things in agriculture, shining a light on gaps in standardization and demonstrating options for scaling. To achieve this, it operates a platform that provides all of its stakeholdersopen access to digital innovations in the agricultural realm. The focus group is coordinated by Dr. Sebastian Bosse and Dr. Ramy Ahmed Fathy (National Telecommunications Regulatory Authority of Egypt). It was established by the ITU and the Food and Agriculture Organization of the United Nations (FAO) in 2021.

Career opportunities: working at Fraunhofer HHI

We're shaping the future.

As a research institute with an international standing, Fraunhofer HHI offers attractive career opportunities.

State-of-the-art laboratories and workplaces in the heart of Berlin

It provides researchers from the fields of science, engineering, informatics and economics the chance to collaborate on exciting projects with a national and international scope. Furthermore, they benefit from outstanding working conditions plus state-of-the-art laboratory facilities.

Students, graduates and young professionals are able to gain an early insight into the various areas in which Fraunhofer HHI operates and then jump straight into their own careers. They can even apply to write a bachelor's, master's or doctoral thesis at the institute.

Employees at Fraunhofer HHI benefit from a great deal of autonomy in the work they undertake, as well as flexible working hours and the possibility of working from home. Child-friendly office facilities also make it easier to combine work and family life. Additionally, yoga courses, massages and much more are on offer to help staff stay healthy.

Quality management

For its research, development and production activities in the areas of photonics and electronics, Fraunhofer HHI has developed and implemented a quality management system that is compliant with DIN EN ISO 9001:2015. Recertification takes place regularly. The institute most recently underwent this process at the start of 2022 and was shown to have met all the requirements of the standard.

Continuing education

Our employees are continually given opportunities for professional and personal growth. The institute offers training and education on a range of subjects, and employees are able to choose the right options for their needs according to their career stage and subject of interest.

Vocational training

Fraunhofer HHI offers vocational training in the following careers:

- Business administrator for office management
- IT specialist
- Microtechnology specialist

Promoting young talent

Fraunhofer HHI is passionate about supporting the next generation of scientists. Every year, the institute takes part in the annual Girls' Day event held across Germany, during which it invites girls of school age to visit the institute and gives them an insight into the world of research. Experiments are conducted in the lab and a range of workshops are held to provide girls with a better idea of what STEM careers involve.

Since 2015, Fraunhofer HHI has been working with the Albrecht-Dürer-Gymnasium, a high school in the Neukölln district of Berlin. This collaboration gives the school's female students the opportunity to go on visits or do placements, allowing them to find out more about applied research and supplement the subjects they study with hands-on experiences. As a result, they emerge with a better idea of what career opportunities are available in science and technology.

HR and recruitment

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Despite the pandemic, our experts have managed to showcase their latest research findings at trade fairs and events worldwide, often on a virtual platform.

8
countries
+
25
cities

Where to meet us

Trade fairs

- SENSOR+TEST
- SPIE Photonics West
- GSMA Mobile World Congress
- Optical Fiber Communication Conference and Exhibition (OFC)
- Optics & Photonics Internatio-nal Exhibition (OPIE)
- National Association of Broadcasters Show (NAB Show)
- LASER World of PHOTONICS
- Hannover Messe
- International Broadcasting Convention (IBC)
- European Conference on Optical Communication (ECOC)
- European Conference on Networks and Communication (EuCNC)
- PIC International Conference
- Consumer Electronics Show (CES)
- FUTURAS IN RES

Events

- World Health Summit
- Girls' Day
- ITG-Fachkonferenz (expert conference)
- Photonics Days Berlin Brandenburg
- Auditing AI-Systems
- media:net berlinbrandenburg Talent Festival
- Berlin 5G Week
- Lange Nacht der Wissenschaften
- FMD Innovation Days
- Technology Innovation Day
- ITU-Fokusgruppen Treffen

Contact details

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Branch lab: Fiber-Optical Sensor Systems department

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