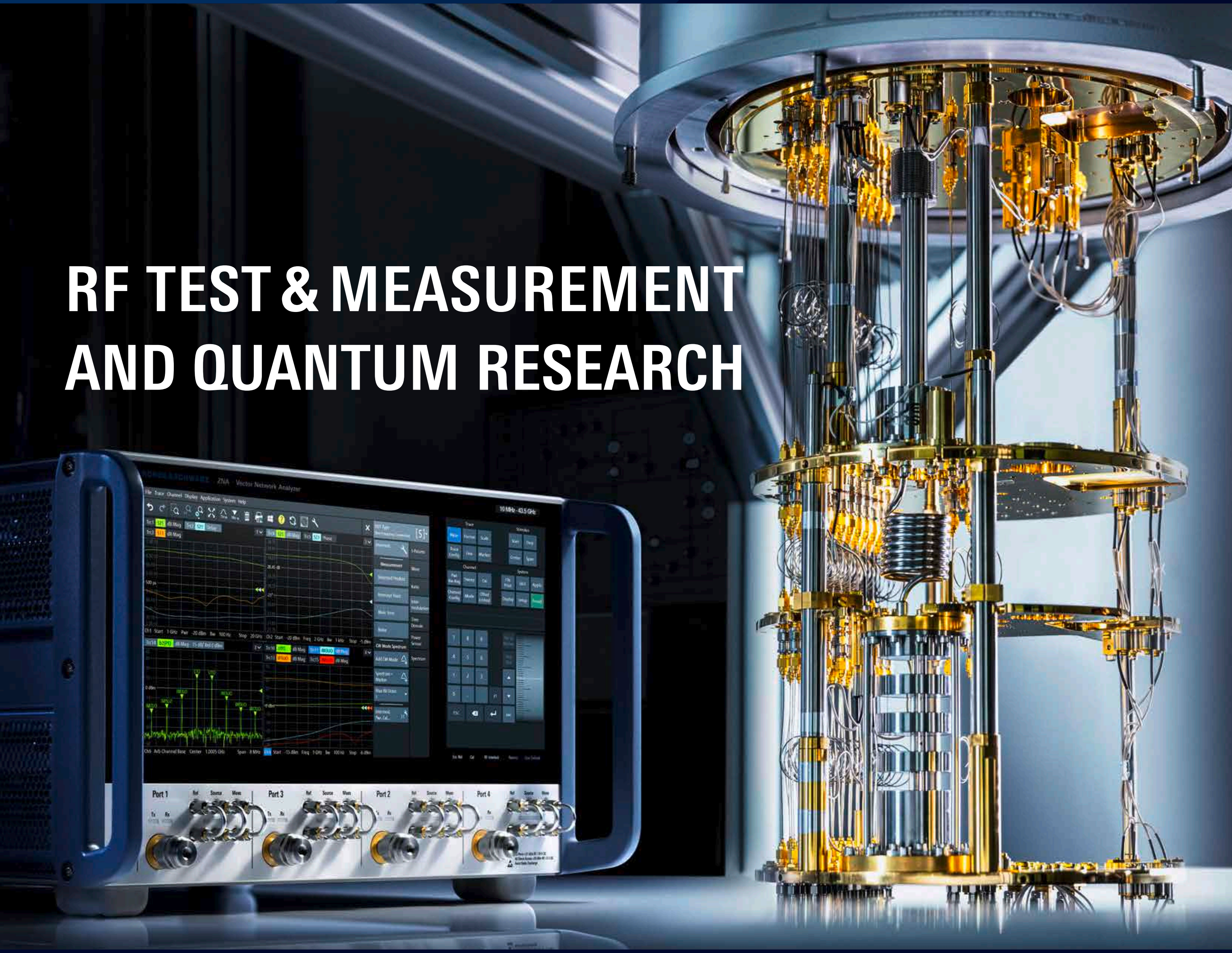
226/2023

NEWS

ROHDE&SCHWARZ

Make ideas real



RF TEST & MEASUREMENT AND QUANTUM RESEARCH

RF test & measurement and quantum computer research

6G: everything will be connected

5 kW HF high-power transmitters for air traffic control

Rohde & Schwarz represents leading-edge technology at the limits of the technically possible. Industry and government customers use our products and solutions to shape their digital and technological sovereignty –

TO ENSURE A SAFER AND CONNECTED WORLD.

MASTHEAD

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COVER FEATURE

Dear Readers,

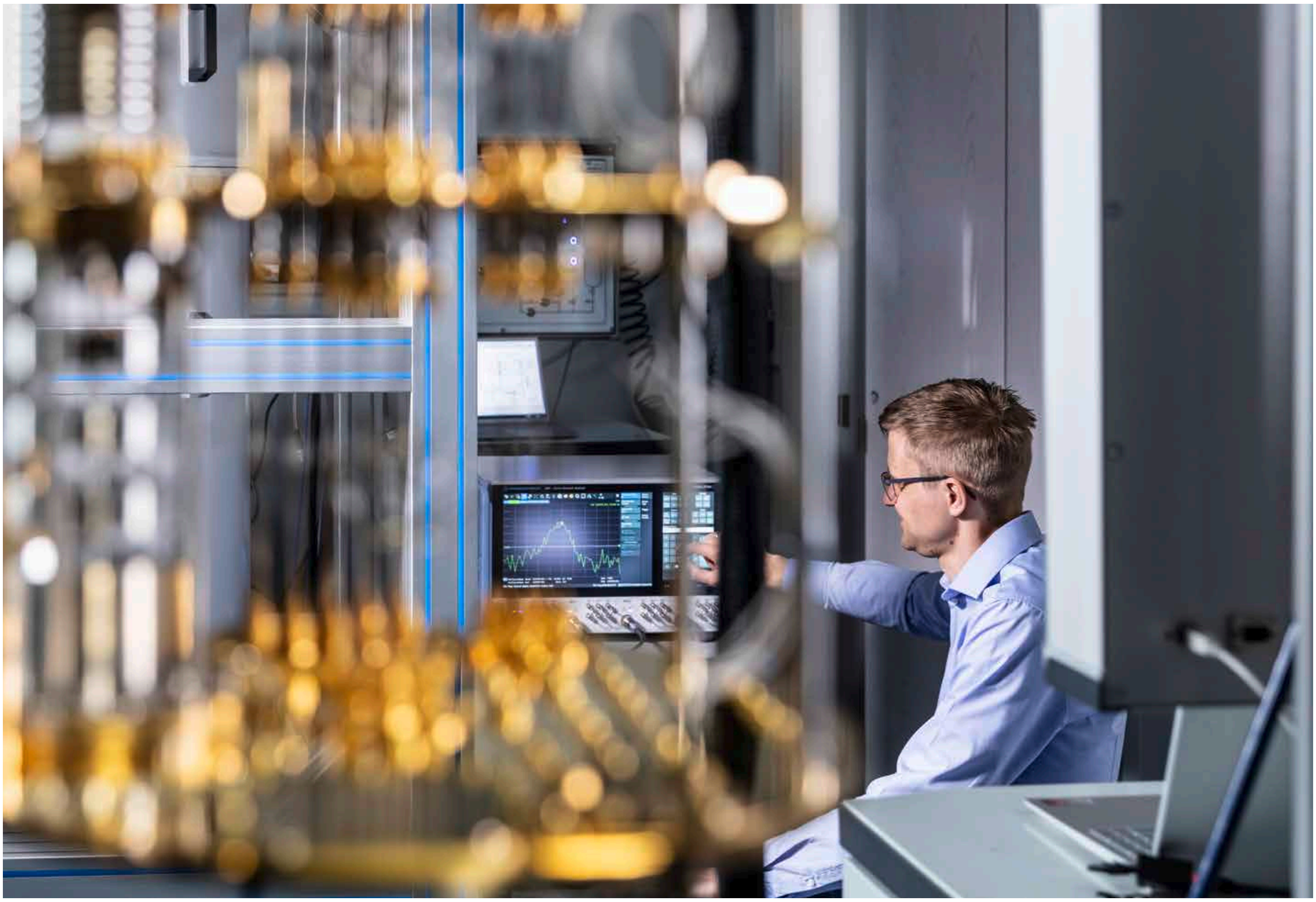
What comes to mind when you read the words quantum technology? You probably think of the awesome computing power of quantum computers. Companies and governments see quantum computing as a key technology and are working hard to develop it. But quantum effects can do much more than give computers superpowers. Research into new generations of both quantum sensors and quantum encryption is well underway. And although still a future vision, the results are beginning to take shape.

Quantum technology plays an important role at Rohde & Schwarz, which is why we decided to take a deep dive into the topic for this issue of NEWS and inspire all of you technology fans. If you have heard a lot about quantum bits but have never actually seen one, I recommend Fabian Kronowetter's article about quantum radar technology on page 24. You will find a microscopic image in his article, which was kindly provided by the Walther-Meißner-Institute. Perhaps you are familiar with this name. The institute is a renowned player in quantum research and has contributed two articles to this issue of NEWS. Institute Director Prof. Dr. Rudolf Gross describes quantum sensors and quantum metrology (page 20), while Max Werninghaus' article (page 12) explains why RF T&M equipment is required in quantum computer research. Quantum cryptography is a real cat-and-mouse game. It's still impossible to say whether quantum computers will render today's encryption methods insecure or whether quantum-secure encryption will emerge in time to save current cryptographic methods. Rather than trying to work that out, our colleagues at Rohde & Schwarz Cybersecurity provide valuable insight into this fascinating topic (page 30).

I hope you enjoy this issue of our NEWS magazine.

Sincerely,

Christian Reiter,
Vice President Corporate Marketing and Communications



12 **RF TEST & MEASUREMENT AND QUANTUM COMPUTER RESEARCH**
Signal generators with high phase and amplitude stability help with research.

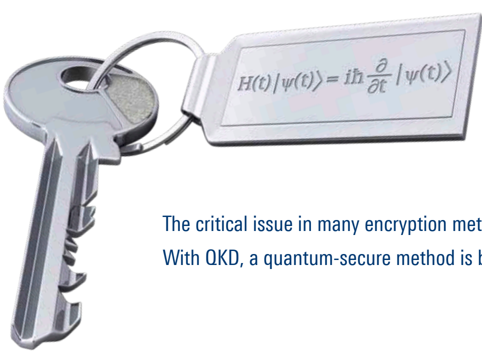
50 **6G: EVERYTHING WILL BE CONNECTED**
If the 6G visions become reality, we can expect a wonderland of communications in the 2030s.

OVERVIEW

NEWS 226/2023

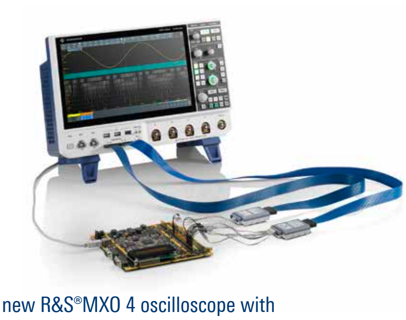
COVER FEATURE

QUANTUM TECHNOLOGY



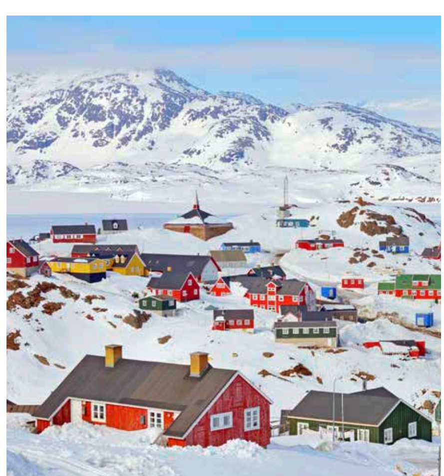
The critical issue in many encryption methods is the secure distribution of keys. With QKD, a quantum-secure method is being developed (page 30).

GENERAL PURPOSE



The new R&S®MXO 4 oscilloscope with mixed signal option (MSO) and DUT (page 38).

MOBILE COMMUNICATIONS



The R&S®SK4105 HF high-power transmitter is ideal for air traffic service under harsh conditions such as those in Greenland (page 70).

AVIATION SAFETY

NEWS COMPACT

SUCCESSFUL FISCAL YEAR 2021 | 2022

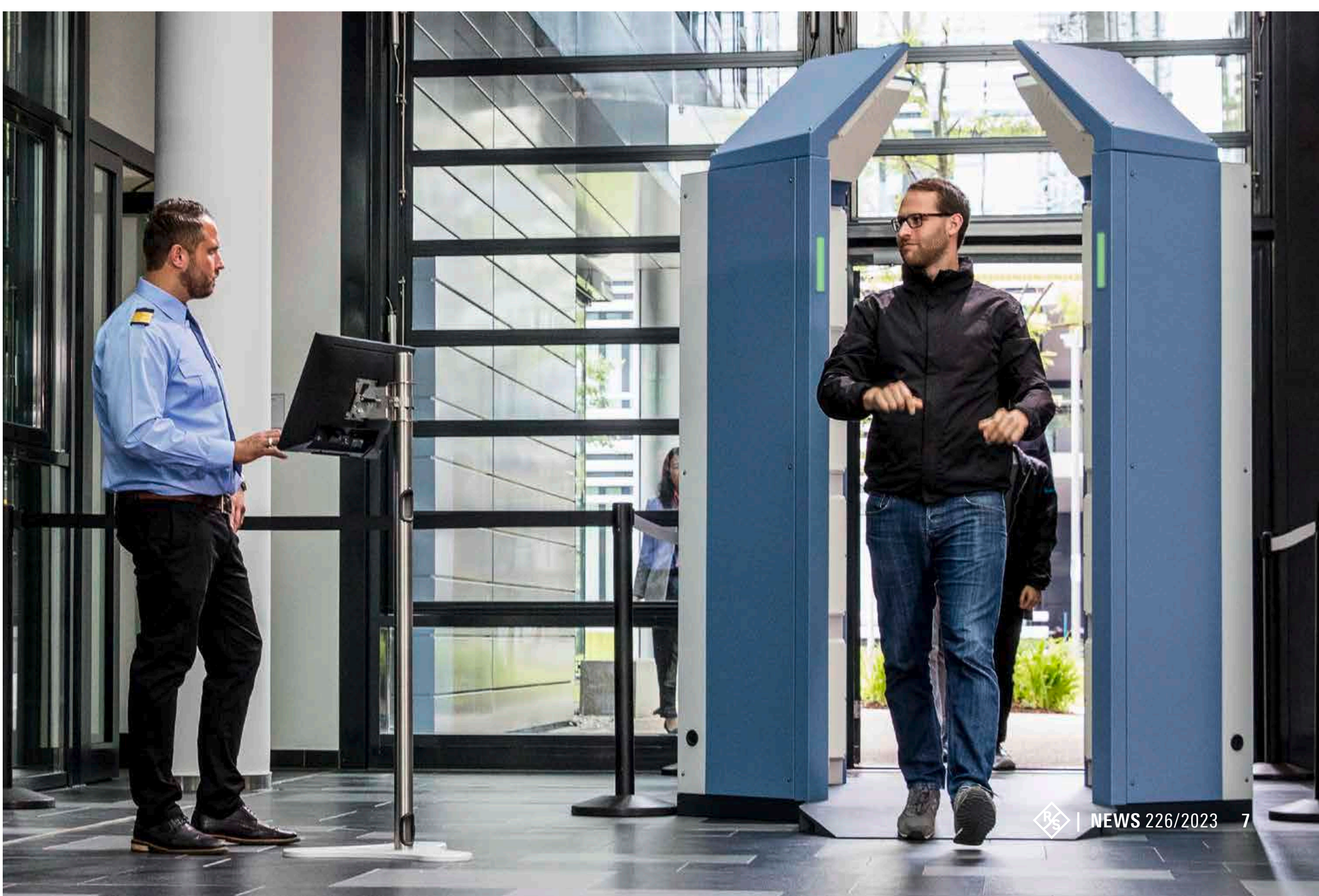
Rohde & Schwarz achieved EUR 2.53 billion in revenue, returning the company to pre-pandemic levels and EUR 2.84 billion in incoming orders for FY 2021/22, exceeding pre-pandemic levels. Test & Measurement, Technology Systems and Networks & Cybersecurity contributed to the positive trend, with each delivering double-digit growth. Growth drivers included the worldwide rollout of 5G networks, research in future technologies such as quantum computers and 6G and major orders in the security and defense sectors. The British Royal Navy awarded Rohde & Schwarz an order to equip the second batch of new City-class frigates with communications systems. An order for a complete Rohde & Schwarz naval communications suite was also secured in Germany for the first time. The company has taken decisive steps to map out a successful future, including the launch of its new R&S®MXO 4 midrange oscilloscope, the R&S®Series5200 ATC radios and the new R&S®TH1 high-power transmitter for broadcasters. The acquisition of analytics solutions provider Schönhofer Sales and Engineering is a sensible addition to the group's signal intelligence portfolio. The R&S®QPS201 security scanner has strong prospects on the US market after being placed on the Qualified Products List of the Transportation Security Administration (TSA).

In September 2022, the R&S®QPS Walk2000 was presented for the first time at Security Essen – Germany's most important civil security trade show.

BEYOND AIRPORTS

For years, R&S®QPS security scanners have been simplifying security checks at airports around the world. The first models were introduced in 2014 and helped speed up the now all-too-familiar airport security lines. Thousands of millimeter-wave sensors rapidly identifies each person in 360 degrees while AI-powered detection software reliably detects dangerous non-metallic items. Each person only has to stand briefly in the scanner in a natural pose. The R&S®QPS Walk2000 is speeding things up even more. As the name implies, people can walk through this security scanner at a normal pace. Even better, nobody has to remove their jacket, coat or shoes because the sensors can also penetrate several layers of clothing. Remarkably, the transmitted power is several orders of magnitude below that of standard smartphones. The R&S®QPS Walk2000 can check 750 people per hour. Quick, hassle-free security checks are also interesting for access to critical infrastructure, large events and loss prevention in manufacturing companies, for example. The R&S®QPS Walk2000 has already passed its first real-world test. French security provider BEHM used the scanner at the Rockhal festival in Luxembourg and was very satisfied with how smooth and easy it made security checks.

The R&S®QPS Walk2000 displays potentially dangerous objects as symbols on a generic avatar. No body shapes are recorded or displayed during checks.

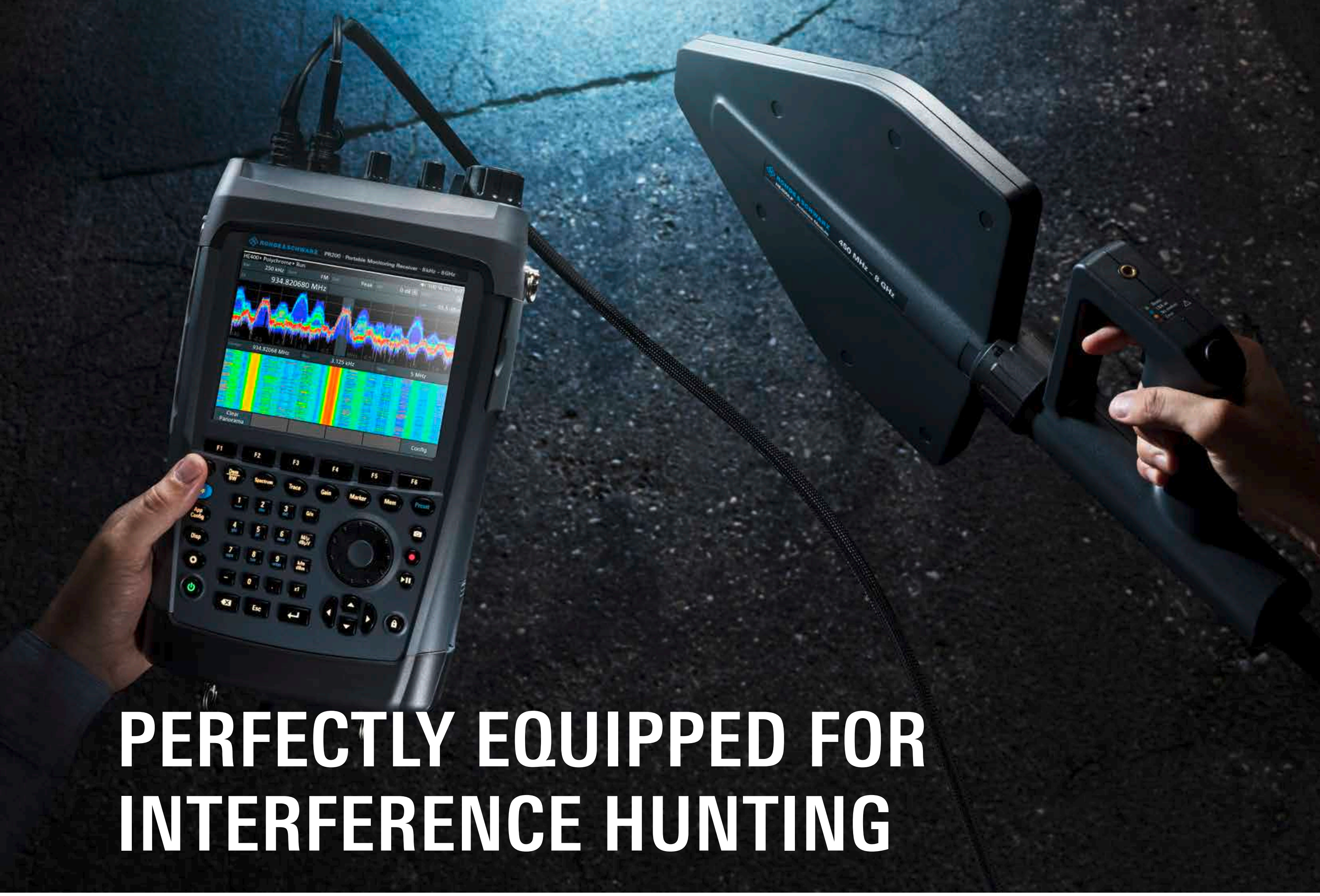


INNOVATIVE AND SUSTAINABLE TRANSMISSION

The transmitter and amplifier stages of the R&S®TH1 high-power transmitter are designed as plug-in modules, and the pump unit for the liquid cooling system is housed in the base.

Streaming content is hugely popular nowadays but there is still demand for conventional television and radio broadcasts. 5G Broadcast combines the best of both worlds and is seen as a next generation media technology. Rohde & Schwarz is committed to developing this technology, and in 2019 we supplied transmitters and network components for the 5G Broadcast field trial in the run-up to the 2022 Olympic Games in Beijing. Industry insiders expect the worldwide rollout to start in 2025, but media providers and network operators can get ready for the future with the new R&S®TH1 high-power transmitter, which operates in the UHF band between 470 MHz and 700 MHz with 9.6 kW transmit power in the maximum configuration. The software defined exciter supports current DVB-T and DVB-T2 digital TV standards and can be extended to 5G Broadcast with no hardware changes. Efficient liquid cooling increases transmitter reliability and significantly reduces both overall energy consumption and the CO2 footprint of transmitter networks. This creates an attractive way for radio broadcasting network operators to meet their climate goals. Along with streaming media content, 5G Broadcast enables reliable, low-threshold distribution of public emergency notifications, traffic data and software updates for IoT devices and autonomous vehicles. The R&S®TH1 is the first member of a new transmitter family that Rohde & Schwarz will expand with more models in the coming years.

The basic configuration of the R&S®TH1 high-power transmitter can be controlled through an HTML5 web user interface. It is shown here with the optional touch display.



PERFECTLY EQUIPPED FOR INTERFERENCE HUNTING

When a mobile network provider reports service disruptions from unknown sources, specialists from the German federal network agency for electricity, gas, telecommunications, post and railway (Bundesnetzagentur) are sent to investigate the cause, often leading them up to rooftops, down narrow paths and other places only accessible on foot.

The federal authority relies on the R&S®PR200 portable monitoring receivers to track down interference sources. After an initial order of 62 devices, Rohde & Schwarz delivered another twelve in November 2022. The controls have the same logic as the previous model, the R&S®PR100, which the Bundesnetzagentur was already using. This eliminated the need for retraining. New is the feasibility of time domain measurements in addition to frequency domain measurements, opening up a whole new range of mobile spectrum monitoring opportunities. Some interference signals cannot be differentiated from wanted signals in a conventional spectrum display but can be separated in the time domain. This is especially true for LTE and 5G signals based on time division duplexing (TDD), where uplink and downlink transmissions are sent over the same channel and share the same frequency band. In a conventional spectrum display, unwanted signals in the weaker uplink signal can be overlaid and masked by strong wanted signals in the downlink. Rohde & Schwarz has integrated a gated spectrum function into its monitoring receivers, allowing users to select a signal section in the time domain and display it side by side as a signal spectrum up to 40 MHz. Interference in modern cellular signals can now be identified with portable monitoring receivers instead of expensive and less mobile equipment. This was also a key requirement for the Bundesnetzagentur.

The R&S®HE400DC handheld directional antenna expands the standard 8 kHz to 8 GHz bandwidth of the R&S®PR200 up to 20 GHz.

ISO 27001 FOR THE BENELUX LOCATION

Manufacturers often require sensitive information from their customers such as design drawings or test data. To document the proper handling of this information, processes can be certified in line with the ISO 27001 standard, the world's most important information security standard. The five German Rohde & Schwarz locations in Munich, Stuttgart, Teisnach, Berlin and Hamburg were certified in 2021 and were followed in August 2022 by Rohde & Schwarz Benelux B.V. in Utrecht, the Netherlands. The office of the German technical certification provider TÜV performed the audit. It does not include all information management activities, just those relevant in the segments covered by the certification application and the operation and administration of the internal IT services and other support processes. Rohde & Schwarz Benelux was certified for engineering services in industrial electronics, their maintenance, calibration and other activities. ISO 27001 is increasingly important when selecting suppliers; especially for customers from the critical infrastructure and secure communications segment.


TÜV NEDERLAND

Rohde & Schwarz Benelux B.V.

Utrecht (The Netherlands)

The information security management system of Rohde & Schwarz Benelux B.V. and the application thereof complies with the requirements as stipulated in the standard:

NEN-EN-ISO/IEC 27001:2017+A11:2020

This is in accordance with the Statement of applicability version 1.0 of 14/04/2022.

Evaluation of the information security management system took place in accordance with TÜV Nederland's certification regulations for the field of application:

Information Security related to: provisioning, training and engineering services, maintenance, verification and calibration of electronic and IT related products and systems, used in Industrial Electronics, Aerospace, Defense, Security, Broadcast & Media and Cybersecurity.

This certification is subject to annual evaluation by TÜV Nederland.

Registration number: 31088-1.1
Start date certificate: 11-08-2022
Certificate valid until: 11-08-2025
Date of first certificate: 11-08-2022

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ISO 27001

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ISO 27001 certificate for Rohde & Schwarz Benelux.

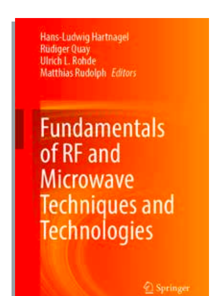
The IEEE honored Prof. Rohde with the Photonics Society Engineering Achievement Award.

IEEE AWARD FOR PROFESSOR ROHDE

The Institute of Electrical and Electronics Engineers (IEEE) honored Prof. Dr.-Ing. habil. Dr. h.c. mult. Ulrich L. Rohde for his outstanding engineering achievements in the field of optoelectronic signal generation and optical T&M equipment for next generation smart optical networks with the Photonics Society Engineering Achievement Award. The award includes a cash prize and a medal recognizing extraordinary technical accomplishments with a significant impact on the development or commercial application of laser or electro-optic technology over the past 10 years. It was presented to Prof. Rohde at the IEEE Photonics Conference in Vancouver, Canada, in November 2022.

NEW TEXTBOOK BY PROFESSOR ROHDE

Prof. Dr.-Ing. habil. Dr. h.c. mult. Ulrich L. Rohde published a textbook on radio frequency and microwave technology with three other authors. The Fundamentals of RF and Microwave Techniques and Technologies is based on the German-language textbook published in 1965. Along with advanced, industrially relevant methods for analyzing and designing RF and microwave circuits, the book also describes the underlying theoretical details. The 1576-page work has been published by the Springer Verlag and is intended for students and teachers as well as working engineers.



The new book on the theory and practice of RF and microwave engineering for teachers and scientists as well as working engineers.

LOCK-IN AMPLIFIERS UP TO 8.5 GHz

Generating and measuring microwave signals above 1 GHz was once the role of network analyzers, spectrum analyzers, oscilloscopes and signal generators. Two lock-in amplifiers from Zurich Instruments have now been added to the conventional RF T&M product range. The GHFLI measures and generates signals up to 1.8 GHz and the SHFLI up to 8.5 GHz. They are the first commercial lock-in amplifiers with frequency ranges above 600 MHz. The Swiss company has been part of Rohde & Schwarz since the summer of 2021 and has received requests for such devices from product development as well as fundamental and applied research. Generally speaking, lock-in amplifiers are excellent at measuring weak signals in the presence of a strong noise floor. Both models from Zurich Instruments now make these features available to a broad range of applications, such as R&D departments for MEMS sensors or for reading out quantum bits in quantum computer research. Practical and timesaving: up to eight frequencies can be measured simultaneously with GHFLI and SHFLI. They can be operated using LabOne® control software from Zurich Instruments either with a graphic user interface or industry-standard programming interfaces. They have a built-in two-channel oscilloscope and spectrum analyzer, saving lab bench space. More product details, including an interesting webinar, are available on the Zurich Instruments website.

T&M EQUIPMENT FOR PARTICLE ACCELERATOR IN SOUTH KOREA

The official capital of South Korea is Seoul but Sejong is the unofficial capital. Many ministries and agencies have relocated here from Seoul and the planned city, which officially opened in 2012, is also home to the country's first Institute for Accelerator Physics. Current students – even those early on in their studies – can access particle accelerators and gather practical experience. Starting in spring 2023, they can also get hands on experience with Rohde & Schwarz RF T&M equipment that monitors particle beams. Monitoring these beams requires the precise generation and readout of RF signals in the gigahertz range. The University of Korea chose the R&S®SMB100B and R&S®SMA100B signal generators, which can generate signals up to 6 GHz and 20 GHz. The R&S®ZNL20 network analyzer, the most compact instrument in its class, will be used to make S-parameter measurements, while the R&S®RTO6 and R&S®RTM3004 oscilloscopes will be used for signal measurements. The Institute for Accelerator Physics is part of the Sejong Campus of the University of Korea, one of the top 50 universities in Asia.

R&S®RTO6 oscilloscope with 15.6" touchscreen (top) and R&S®SMA100B signal generator (bottom).

RF TEST & MEASUREMENT AND QUANTUM COMPUTER RESEARCH

Current quantum computer research would be impossible without signal generators with high phase and amplitude stability. Instrument manufacturers are working closely with the scientific community to better understand how to prepare and select quantum bits and determine which instrument functions can help with research.

To solve complex problems, quantum computers exploit natural quantum properties. As with conventional bits, logic states are represented and processed using quantum bits (qubit). Whereas a conventional bit is binary, a qubit can simultaneously exist in combinations of two states. This phenomenon is known as superposition and cannot be explained using the laws of classical physics. Superposition is a purely quantum mechanical property and is the basis for the enormous computational potential of quantum computers.

Superconducting qubits

Research currently focuses on the technical implementation of qubits. One promising area is superconducting qubits that use electrical circuits to store electromagnetic fields with a very long half life thanks to their loss-free superconductivity. A resonant circuit is designed to effectively produce a controllable two-state system. The resonance frequency for this type of circuit is typically in the microwave range at 5 GHz. The base state of the resonant circuit is logic state zero, while the first excited state is logic state one.

Systematic control of these two states is still not possible without added structures. In harmonic oscillators, such as LC resonant circuits, the spacing between two adjacent energy states is always equal (harmonicity). One side effect is the uncontrolled shifting of a resonant microwave signal in a circuit either from the base state to the first excited state, or from an arbitrary excited state to the next higher state. Nonlinear inductances can cancel out harmonicity. Josephson junctions help create two distinct energy states that can be used as a controllable qubit. They give the transition from the base state to the first excited state a characteristic frequency that is unique to this transition. Because the property mimics atomic electron transitions, superconducting qubits are also known as artificial atoms.

A quantum state is extremely fragile. The operating temperature for a superconducting qubit is around 10 millikelvin or about –273 °C, which is very close to absolute zero. This is the only way to keep the thermal background noise low enough to avoid uncontrolled stimulation of the quantum state. Here, the thermal noise

Research institutions use the R&S®SGS100A SGMA RF source for high-precision control of quantum computers.

associated with the control signals must also be taken into account (see "Suppressing thermal noise in control signals" at the end of this article).

Controlling quantum states with microwave signals

The energy state of a qubit can be controlled with external microwave signals. A Bloch sphere illustrates this process (Fig. 1, right). The one and zero logic states are located at the north and south poles of the Bloch sphere. Every other point on the surface of the sphere corresponds to a superposition state. Without any external control signal influence, the qubit remains in its base state. Interaction with a resonant microwave signal causes rotation of the state vector in the Bloch sphere. To perform dependable computing operations with qubits,

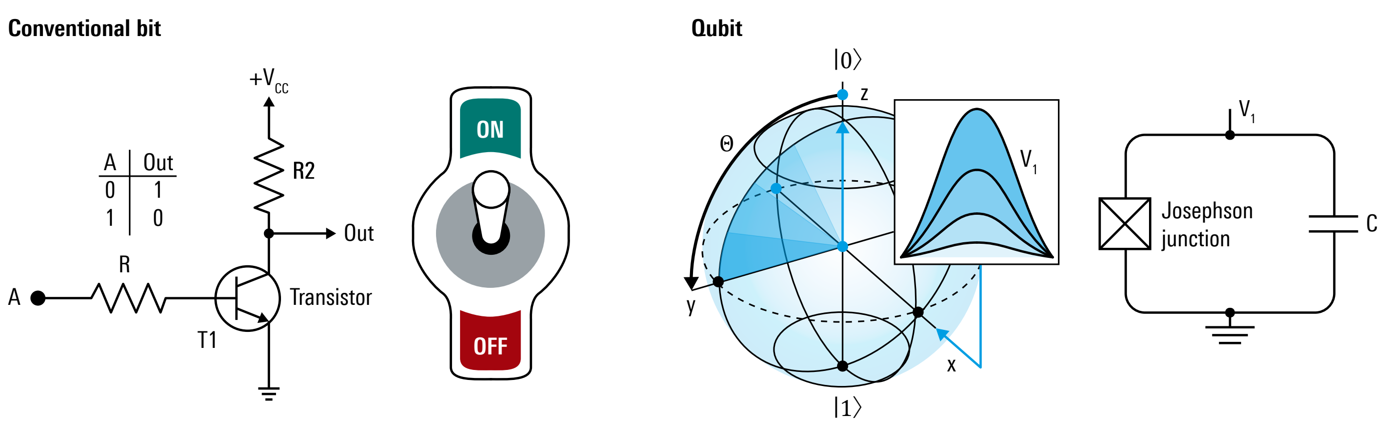


Fig. 1: A conventional bit works with a fixed state (A) and always performs the same operation (in this example, an inverse operation). It is equivalent to a traditional switch. By contrast, the state of a qubit depends on the state of the circuit and control signals can be used to induce various computing operations. The resonant microwave signal V_1 causes the state vector to rotate on the x-axis of the Bloch sphere. The duration and intensity of the signal determine the angle of rotation.


ROHDE&SCHWARZ

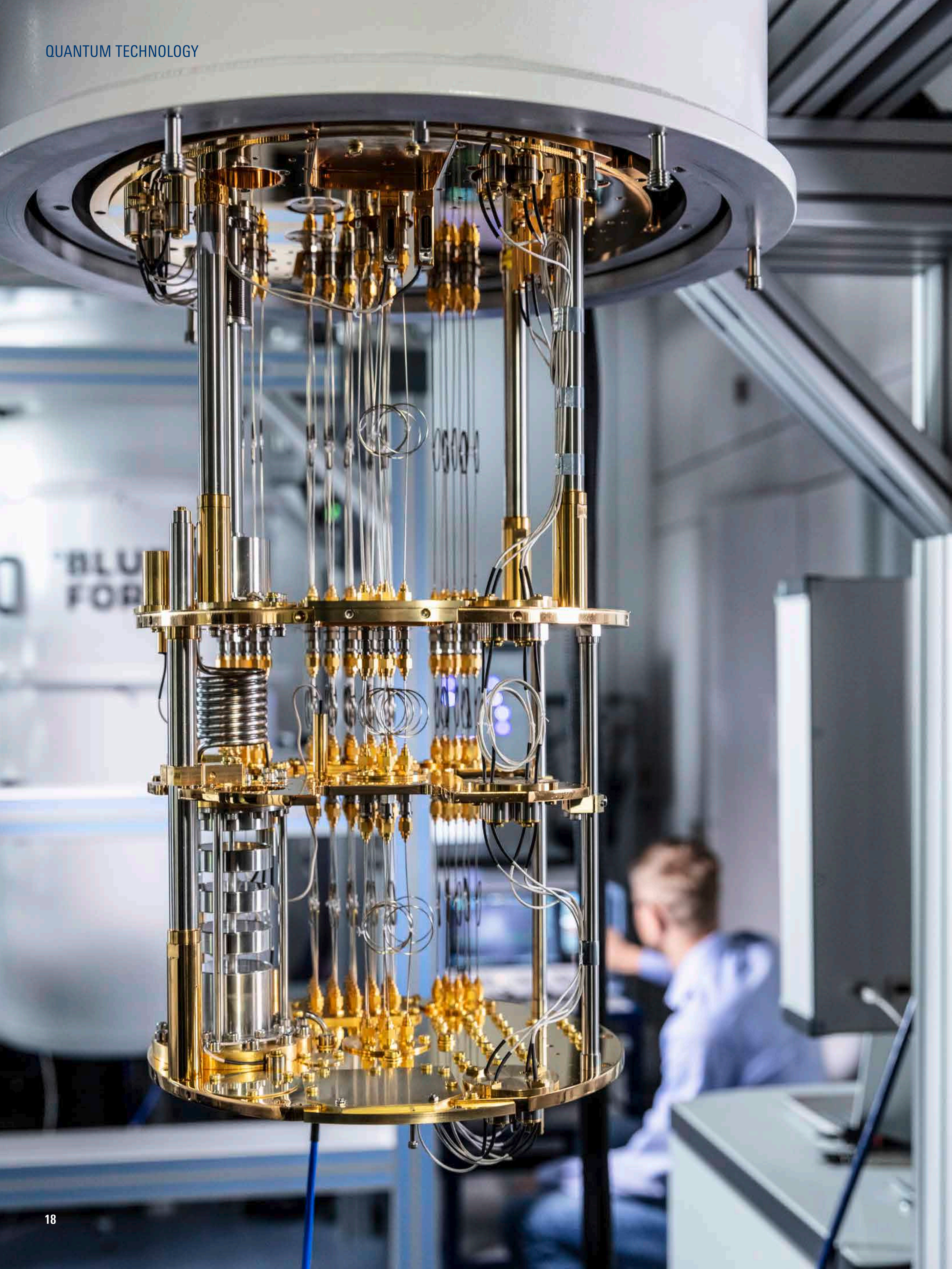
this rotation needs to be controlled with great precision based on the pulse length, microwave signal amplitude and the control pulse envelope. The latter is typically Gaussian, but must be fine-tuned to qubit-specific characteristics. Another important control signal property is the relative phase of the control pulse, which influences the rotation axis of the qubit state in the Bloch sphere. When pulses with the same phase are applied to the qubit, the state always rotates on the same axis (e.g. the x-axis). Changes in phase also change the axis of rotation. If a pulse is phase-shifted by 90°, the state vector will rotate on the y-axis.

Arbitrary waveform generators are reliable, flexible control signal sources. Together with microwave sources and mixers, the right pulses can be generated at the right qubit frequency. By precisely regulating the control pulse phase in real time and exact control of the envelopes, any desired target point on a Bloch sphere can be reached at any time from any starting point. A complete set of control operations consists of 90° rotations in combination with arbitrarily controllable carrier signal phases.

Signal source requirements

Unlike conventional computing operations with a high error tolerance, quantum computers rely on precise calibration of control pulses. Even tiny deviations in the rotation (over rotation of the quantum state by 1%) can alter the resulting quantum operation. Similar errors occur with inaccurate phase control. Control instruments for quantum computers must therefore have high phase and amplitude stability. Control pulse phases are regulated by the in-phase and quadrature components of the pulse stored on the arbitrary waveform generator.

Quantum algorithms and quantum computer experiments are complex. Both require output of a large number of signal pulses on multiple channels with relevant phase stability and timing synchronization. This often leads to long wait times during initialization of conventional control hardware and can ultimately limit the complexity of planned experiments. Various manufacturers of microwave generators have recently begun developing special instruments together with quantum computing scientists. These instruments can do much more than conventional arbitrary waveform generators and satisfy some of the special research requirements in this field. Pulse phases can be managed directly on the instrument with field programmable gate arrays (FPGA), drastically reducing the required storage space. And even complex quantum algorithms that involve thousands of operations can be reduced to a manageable set of fundamental operations. There is no need to store a continuous signal in the arbitrary waveform generator for each quantum algorithm. A set of fundamental operations along with information about the output sequence are enough. Specialized arbitrary waveform generators for quantum computer research already support such functions.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Signal analysis for selecting quantum states

Once a quantum computer runs an operation, the quantum states of the qubits are selected and the qubits are coupled to readout resonators. Due to interaction with the qubit, the resonance frequency of the resonator is shifted depending on the qubit state (Fig. 2). By stimulating it with a readout signal near the resonance frequency, it becomes possible to deduce the qubit state based on the shift in the signal's amplitude and phase in transmission or reflection.

Current quantum technology advances allow effective operation of the relevant control electronics and quantum hardware. By directly integrating signal analysis functions into instruments, quantum algorithm results can be observed in real time. Intelligent arbitrary waveform generators simplify working with quantum computers in the same way that assemblers have long been used in computer and machine programming. One of the main challenges here is synchronizing and coordinating the hundreds of signals needed to operate larger quantum computers.

MAX WERNINGHAUS, PhD CANDIDATE
AT THE WALTHER-MEIßNER-INSTITUTE

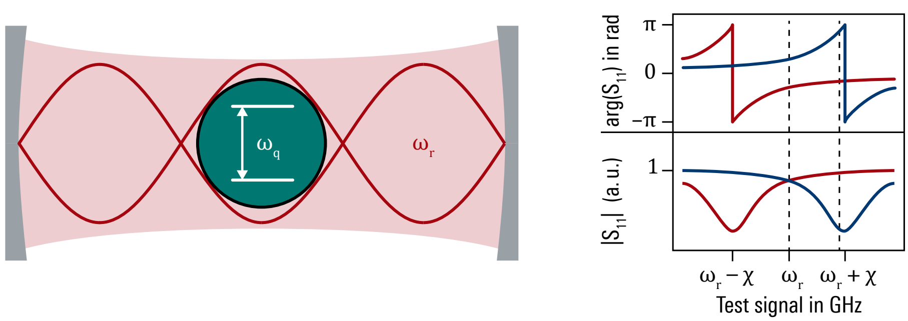


Fig. 2: The two systems mutually influence each other through the interaction between the qubit and resonator (left). Depending on the qubit state (blue and red curves), the resonance frequency ω_r shifted by a certain modulus χ. Using a test signal, the transmission and reflection properties of the resonator can be determined – and thus the state of the qubit. The argument and modulus of the S-parameter S_{11} are plotted on the right.

SUPPRESSING THERMAL NOISE IN CONTROL SIGNALS

Qubit cooling management needs to take into account the immediate vicinity, but also the control signals. Since the signal generators are located outside the cryostat and operate at room temperature, the thermal noise of the control signals is much too high. They must be attenuated at the individual temperature levels so that photons are largely suppressed at the qubit transition frequency. Typically, signal attenuation of about 100 dB is required. Fortunately, quantum circuits require very low input power so that a signal strength of 0 dBm at room temperature is sufficient.

The figure on the left shows a cryogenic setup with low-temperature signal lines. During operation, the temperature of the individual horizontal plates are 1000 mK, 100 mK and 10 mK, from top to bottom. The microwave signals are thermalized at each level to eliminate thermal noise from higher temperatures and reduce the effective noise temperature to a particular level.

SUPER POSITION: VAST STRIDES IN QUANTUM SENSORS AND QUANTUM METROLOGY

Researchers can create well-defined quantum systems and have learnt to precisely control and read out quantum states. This raises hopes for a new generation of computers and high-precision sensors with much shorter measurement times. Research into quantum sensor technology and quantum metrology is currently making great progress.

Sensors play a key role for humanity. They can collect massive amounts of measurement data imperceptible to human senses. The amount of raw sensor data has grown so much recently that it is practically impossible to analyze it all without intelligent analysis technologies that help extract useful information from the huge amount of data.

The goal of improving sensors to open up new applications is as old as sensor technology itself. Quantum phenomena such as superconductivity and magnetism were exploited early on and high-resolution quantum sensors have been successfully used for decades. With this in mind, it is surprising to see research activity surge in this mature technological field.

New interest in quantum sensors

The strong focus on quantum technologies in fundamental research, industry and politics is generating feverish interest in quantum sensing. The reason is simple: recent progress in engineering well-defined quantum systems has taught researchers how to control and manipulate them and how to accurately read them out. If quantum systems react sensitively to environmental variables such as electrical and magnetic fields, temperature or acceleration, measuring changes in the state of these quantum systems allows to precisely determine these variables.

Quantum sensors are able to accurately measure environmental variables based on changes in quantum system states. The basic requirements for quantum sensors are:
- The sensor must be formed by a quantum system with discrete energy levels.
- The ability to initialize the quantum system in a well-defined state and ability to manipulate and read out the quantum state.
- The quantum system must show pronounced dependence between its state and environmental parameters.

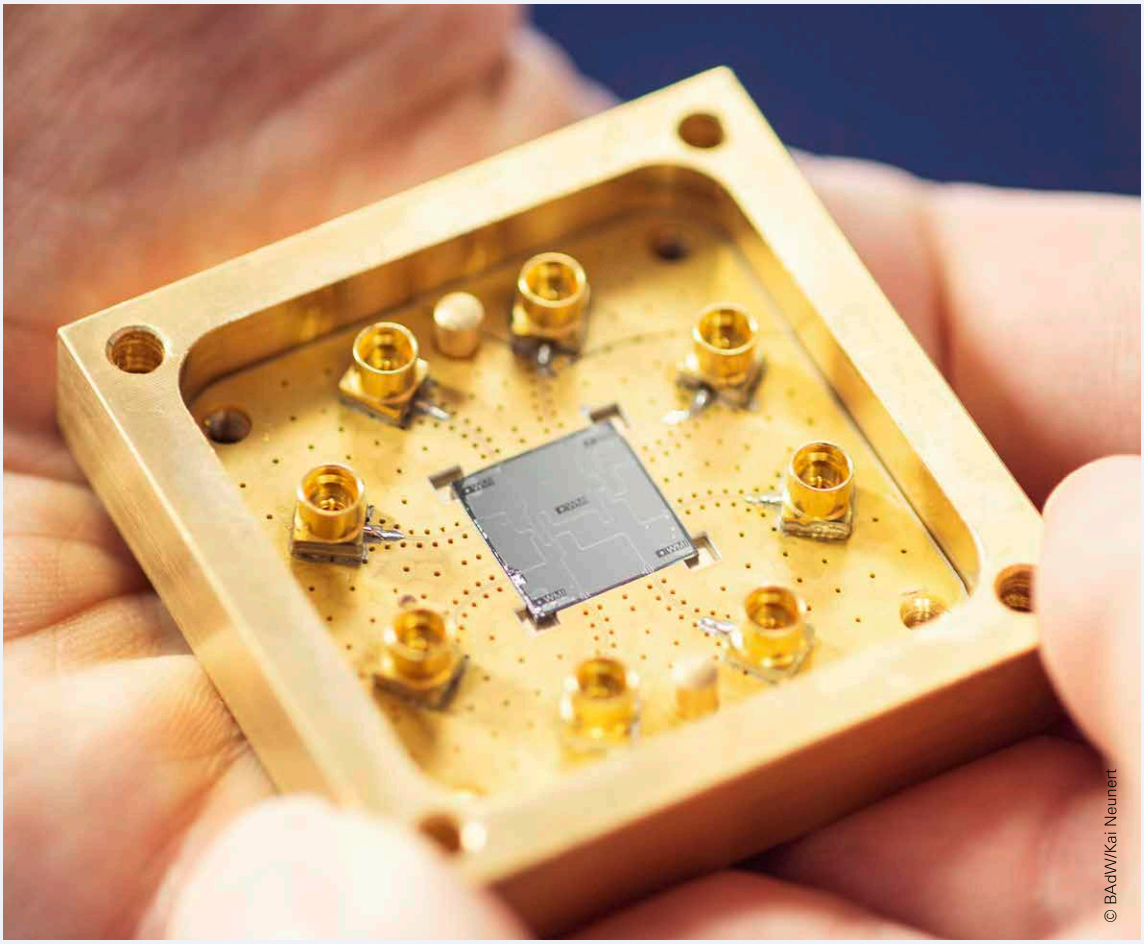
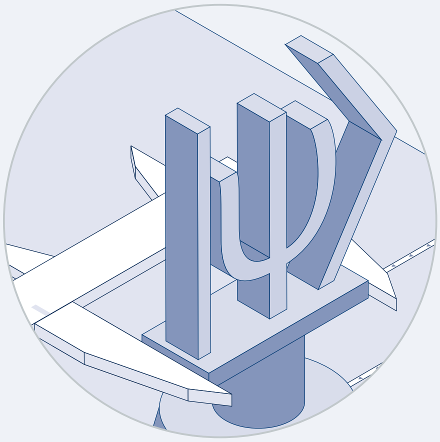


Fig. 1: Manufactured at the Walther-Meißner-Institute: the chip in the RF housing has several superconducting circuits.



Fortunately, nature provides a number of quantum systems that satisfy these requirements, including atoms, ions and atomic clouds that can be captured with suitable traps. A second class includes atom-like defects in solids, such as the nitrogen-vacancy centers in diamonds that are often used in quantum sensors. Sophisticated technologies are already available for both classes that allow coherent manipulation and control. In many cases, they are based on continuous and pulsed laser and microwave signals.

Where quantum sensors and quantum computers benefit from each other

The rapid progress in research makes it possible to artificially create customized quantum systems using well-established solid-state technologies. In this way, quantum systems can be optimized for sensor applications. Some well-known examples include nanomechanical, superconducting and spin based systems. These quantum systems can also be used in quantum computers. Strictly speaking, quantum computing and quantum sensors are two distinct research fields. Quantum systems for computers should be insensitive to environmental parameters, whereas the opposite is true for sensor applications. However, a clear overlap is present in the development of techniques for manipulating and controlling quantum systems. Here, the two fields can benefit greatly from one another.

Quantum metrology and shorter measurement times

Quantum metrology is a field more closely associated with quantum sensors. Both fields aim to measure and determine the state of a given system – either a conventional or a quantum system. In particular, the readout of a quantum sensor can be assigned to the field of quantum metrology.

In quantum physics, Heisenberg's uncertainty principle sets a fundamental limit on measurement precision. The Heisenberg limit dictates that measurement accuracy increases with measurement time t or number of measurements N, but not faster than 1/t or 1/N. Moreover, the Heisenberg limit can only be reached if there are quantum correlations among individual measurement events. This can be achieved using unconventional signals such as squeezed quantum states. However, care must be taken that the quantum correlations are not destroyed by environmental disruptions during the measurement process. Without quantum correlations, only the standard quantum limit can be attained. Here, measurement precision scales only as $1/\sqrt{N}$. Quantum radar is a typical example (see article "Quantum correlation improves radar technology" on page 24), where the signal-to-noise ratio can be improved by quantum correlations generated with squeezed microwave states.

An interesting example for the application of quantum sensing in fundamental research is the detection of gravitational waves now pioneering new insights into gravitational physics. If laser interferometers used as gravitational wave detectors work with squeezed light instead of conventional coherent laser light, they would have much better resolution with the same measurement times.

While current applied research in quantum metrological techniques aims to reach the Heisenberg limit, the latest research results suggest that it might even be possible to overcome this limit. This would require quantum-correlated states where individual particles (photons for squeezed light) interact with one another.

Fig. 2: Cryostats like this one hold superconducting circuits operating at temperatures close to absolute zero.

Strong national research landscape, international user market

The importance of sensors and metrology in science and technology has generated a huge international interest in improving sensors and measurement procedures by employing quantum technologies. Therefore, quantum sensors and quantum metrology are also key research areas at the Munich Center for Quantum Science and Technology (MCQST), a cluster of excellence funded by the German Research Foundation, and the Munich Quantum Valley e.V. (MQV), the Bavarian flagship project for quantum science and technology. Since the quantum systems used in quantum sensors and quantum metrology are less complex than those needed in quantum computers, practical applications in these areas should come sooner. The application fields are diverse and include microscopy, medical imaging, radar technology, positioning systems, sensors for electric and magnetic fields, geoprospection and seismology, and even gravitational wave detectors and more precise atomic clocks and spectroscopes.

The strong support for quantum sciences and quantum technologies in Germany has triggered huge progress in quantum sensing and metrology, both on the fundamental science and engineering levels. It is time to transform these achievements into successful commercial products.

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FABIAN KRONOWETTER, ROHDE & SCHWARZ

QUANTUM CORRELATION IMPROVES RADAR TECHNOLOGY

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Radar technology has advanced and been optimized over the decades. Current research focuses on expanding the fundamental performance limits of the technology. Potential applications range from aviation to medical engineering. The means: quantum technology.

Radar (radio detection and ranging) technology is high-performance contactless remote sensing of nearby and remote objects using microwave-range electromagnetic waves. It is the cornerstone of many practical applications, including space exploration, raw material development as well as the detection, identification and tracking of objects.

Radar technology principles

The operating principle is simple: a source emits a directional microwave signal into its surroundings. Objects in the signal propagation path reflect parts of the signal and a receiver detects this reflection. The presence of an object and other properties can be determined from the detected signal. These include the distance from the receiver, the direction of movement and speed. In practice, the receiver will not only detect the wanted signal but also interfering signals, such as unavoidable ambient noise. In particular, a wanted signal can be weakened by absorption, low reflectivity or the large distance to the object that it disappears in the noise floor. Objects cannot be detected below the noise floor threshold. Current radar technology uses advanced signal processing methods to efficiently filter the wanted signal from the noise floor. Methods utilizing correlations between the transmit and receive signals are particularly effective. They improve the signal-to-noise ratio (SNR) and increase the reach and quality of radar measurements. However, they have a theoretical limit.

Quantum mechanics to expand classical SNR limit

Enormous advances in quantum science have raised the question as to whether quantum technology could expand this theoretical limit. The answer: yes, exploiting quantum correlations can, in principle, expand the theoretical limits. The specialist literature refers to this as a quantum advantage. This quantum advantage is not strictly limited to the microwave range and radar systems. In theory, quantum advantage can be gained in all applications that use an imaging principle similar to radar technology. These include medical engineering and spectroscopy applications that use electron spin resonance (ESR) and nuclear magnetic resonance (NMR). Quantum technology is especially attractive for applications that already operate close to the classical SNR limit.

Quantum correlations and quantum radar applications

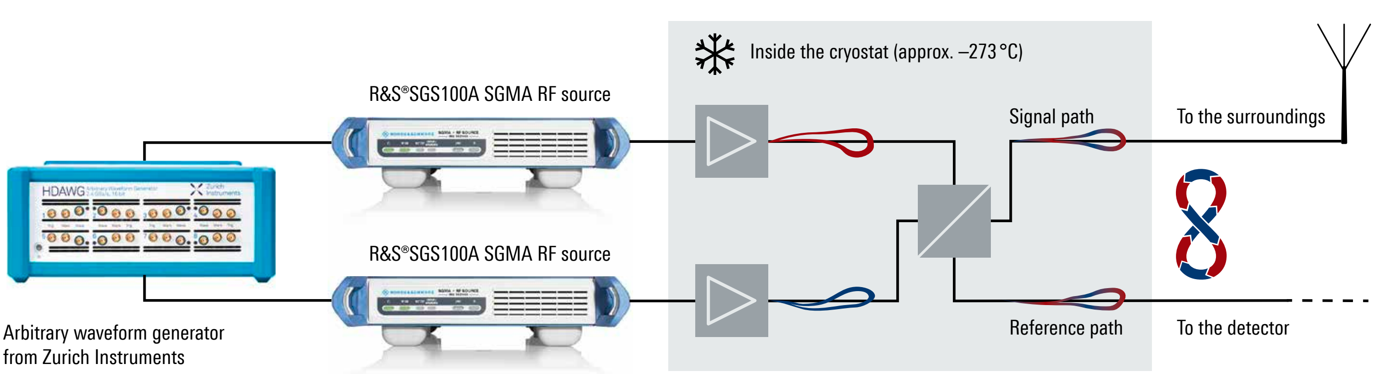
Entanglement and discord are fascinating forms of correlation that can be explained entirely by quantum mechanics. One current quantum radar approach relies on both. Instead of conventional microwaves, it uses entangled microwave signals to detect objects. Researchers at the Walther-Meißner-Institute have been generating these signals for more than 10 years with superconducting circuits. The same circuits, including intelligent cooling, also form the basis for superconducting quantum computers, another research area at the institute. This generates considerable synergies when developing the technology.

Quantum discord is the basis for a very practical quantum radar property: the quantum advantage is not entirely eliminated even if part of the quantum correlation is lost during detection. This is fundamentally important because quantum entanglement is inherently fragile and can easily be destroyed by interaction with the unavoidable noise floor or signal reflection from the object. Nevertheless, a quantum advantage remains. This robustness can be intuitively understood as follows: even though entanglement is lost, more general quantum correlations – the quantum discord – persist between the transmit and reference signal.

Entangled microwaves in quantum radar

When implementing quantum radar, two squeezed states (see "Squeezed states" info box) are generated and superimposed in a beam splitter, resulting in two spatially separated, highly quantum-correlated paths: the signal path and the reference path (Fig. 1). The signal path is emitted to the surroundings as with conventional radar, while the reference path leads directly to the quantum radar detection unit. The two paths, or more accurately the field quadratures P and Q, are entangled (see "Entanglement" info box). Repeated local measurements of the signal path or the reference path will not provide any information about the path concerned. The measurement results have a completely standard distribution and look identical to noise. Remarkably, measuring P in one path provides direct information about Q in the other path. How can we benefit from this interesting phenomenon?

Fig. 1: The signal path and reference path are highly quantum correlated in quantum radar.



Quantum detector for individual microwave photons

Simultaneous measurement is needed: in a quantum detector, the receive signal and the reference signal are mixed in a specific way and subsequently fed to single photon detectors. Superposition of the two signal components in a special mixer converts the remaining quantum correlations into a measurable quantity, which is the number of detected photons. Counting individual microwave photons is a demanding measurement task because of their low energy levels, making microwave single photon detectors a key component of quantum radar. Microwave single photon detectors can be realized using superconducting quantum bits (Fig. 2) and the detectors are so sensitive that they have resolution down to the smallest energy unit of electromagnetic waves, a single photon.

Repeated measurement with the quantum detector delivers two different measurement distributions, depending on whether the receive signal contains part of the transmit signal (which means it was reflected by an object) or the transmit signal is lost (did not encounter an object). If a measurement result can be assigned to one of these distributions, a direct conclusion can be drawn about the presence or absence of an object. Note that this distinction is possible in the quantum receiver even if the receive signal strength is identical in both cases. The acquired information results solely from the correlation between the receive signal and the reference signal.

The entangled transmit signal combined with the quantum receiver forms a quantum radar that has a better SNR with the same transmit power thanks to quantum correlations. The quantum advantage in the proposed detector is better by a factor of 2 (3 dB) relative to the best possible SNR without any quantum correlation. Further improvements are still possible. For example, the 3 dB quantum advantage only applies in the simplest case where two signal modes are entangled. In theory, a larger number of modes can be entangled to increase the quantum advantage in proportion to the number of entangled modes. Numerous research groups around the world are now working to answer open questions.

Challenges and Rohde & Schwarz commitment

Taking advantage of quantum correlations in quantum radar requires an extension of conventional radar theory based on correlation filters and ambiguity functions. This poses several physical and technological challenges, especially in the development of practical quantum radar technology. Current technology can only achieve a quantum advantage for extremely low-power signals, making quantum radar only feasible for short-range applications where transmitters should remain undetected or where broadband interference with mobile communications infrastructure should be avoided. Solutions are needed in the medium term that allow signal levels to increase significantly without destroying quantum properties. Conventional amplifier designs are not suitable for this. A primary short-term goal is the experimental demonstration of quantum advantage in a lab, with the entire experiment carried out in a low-temperature device (Fig. 3, right). Here, the generation of quantum-entangled microwave signals and the quantum detector are fully implemented, while environmental factors and objects can be simulated with suitable components.

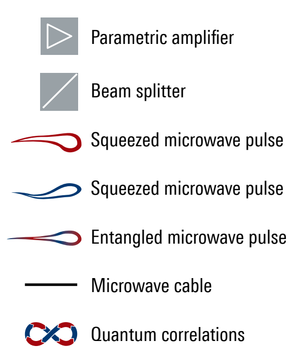
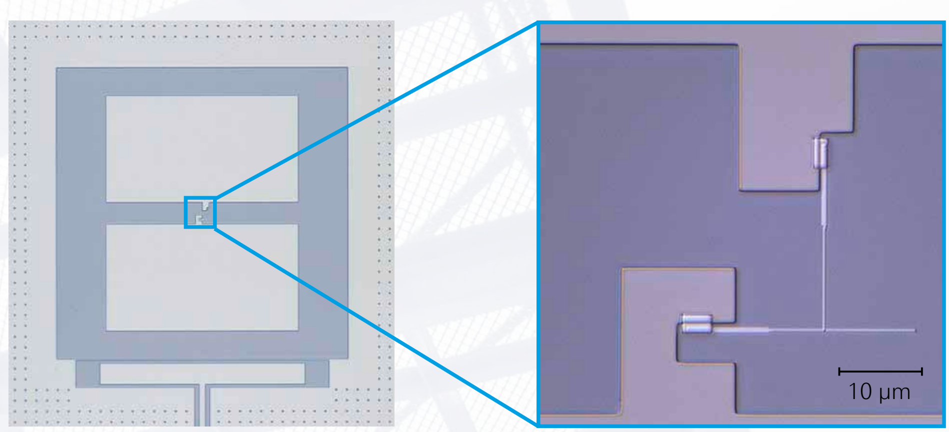


Fig. 2: Microscopic image of a superconducting qubit. The two light-colored rectangles (left) made of niobium provide suitable capacitances and are linked through a nonlinear inductance via an aluminum Josephson junction (right). This creates an LC circuit, effectively forming a two-state system.



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Equipment from Rohde & Schwarz and Zurich Instruments is vital to this experiment. A combination of R&S®SGS100A SGMA RF sources and HDAWG 750 MHz arbitrary waveform generators can be used to generate propagating quantum-entangled microwave signals at a frequency of several gigahertz using superconducting quantum circuits.

These components are also crucial for implementing quantum receivers, both in the mixer and in the single photon detectors. Rohde & Schwarz vector network analyzers, spectrum analyzers and oscilloscopes also allow the setup to be calibrated and characterized in advance.

Many technical challenges must still be overcome for potential applications, such as allowing signal conditioning and signal transmission from low-temperature components to room-temperature components, and systems to be operated under real-world conditions. These challenges are being tackled by a Munich based team from the scientific and industrial sectors as part of the QUARATE project, funded by the German Federal Ministry of Education and Research (BMBF). Rohde & Schwarz is both a partner and coordinator of the project.

FABIAN KRONOWETTER, ROHDE & SCHWARZ

Fig. 3: Measurement setup at the Walther-Meißner-Institute with a cryostat (right) and an R&S®ZNA vector network analyzer (left) for analyzing the resonances of superconducting circuits.

SQUEEZED STATES

At the Walther-Meißner-Institute, squeezed states are used to generate entangled microwave signals for quantum radar. These squeezed states are generated with a superconducting parametric amplifier, which works analogous to a swing where children intuitively increase the amplitude of the swinging motion by periodically raising and lowering their legs to change the effective pendulum length parameter of the swing. In a superconducting parametric amplifier, the pendulum length parameter corresponds to the inductance of a resonant circuit periodically modulated by a pump signal. This amplifies a quadrature P of the microwave signal $P \cdot sin\omega t + Q \cdot cos\omega t$ while at the same time attenuating the orthogonal quadrature Q. According to Heisenberg's uncertainty principle, P and Q cannot be measured simultaneously with any precision; the product of their uncertainties $\Delta P \cdot \Delta Q$ must always exceed a certain minimum. A parametric amplifier can reduce the uncertainty of one quadrature below the zero-point or vacuum fluctuation, at the expense of the orthogonal quadrature. This results in a squeezed state. Getting below the zero-point fluctuations is a prerequisite for realizing a quantum advantage.

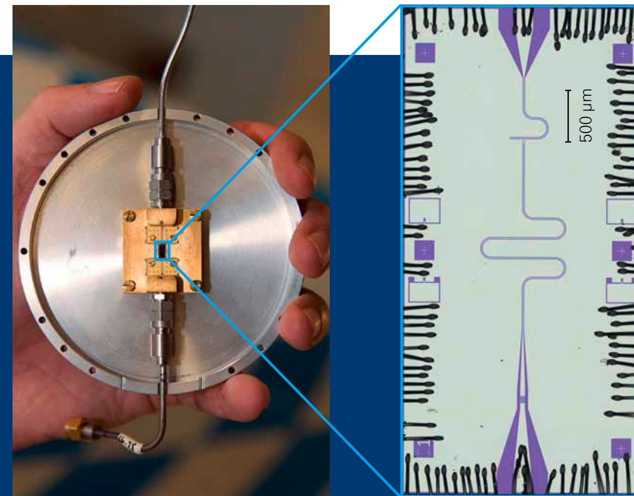


Fig. 4: Structure of a superconducting parametric amplifier.

ENTANGLEMENT

Quantum mechanical correlation effects such as entanglement are not part of our everyday experience. In classical physics, an overall system consisting of, for example, two components can always be clearly separated into these discrete components. The states of these two components (red and blue in our example) are always well defined with the behavior of these two components describing the behavior of the overall system. This is not true for the quantum world, where the overall system can be in a well-defined entangled state but can no longer be described by the distinct subsystems, each with its own well-defined state (e.g. red or blue). Instead, the subsystems are in a superposition of possible states. Entanglement means that each state of one subsystem is linked to a corresponding state of the other subsystem. If a measurement shows that one subsystem is in a red state, the observer knows that the other subsystem is in a blue state. This means the measurement results of an entangled system are correlated. If they were fully independent, both subsystems could be in either blue state or the red state, and drawing any reliable conclusions about one subsystem from knowledge of the other would be impossible.

This phenomenon is called quantum correlation, since it rises above the horizon of classical physics. As the two subsystems can be located at any arbitrary distance, Albert Einstein called the phenomenon of entanglement "spooky action at a distance" and used thought experiments to disprove it. However, it is now accepted as a real phenomenon and is already used in technical applications.

QUARATE

Rohde & Schwarz, the Walther-Meißner-Institute, the Technical University of Munich and the German Aerospace Center have been collaborating on the three-year Quantum Radar Team (QUARATE) project since February 2021. They are investigating the scientific and technical basis for quantum radar and evaluating the prospects for practical implementation. Related fields such as metrology or imaging can also benefit from the project's insights. EUR 3.1 million in project funding is available, three quarters of which comes from the German Federal Ministry of Education and Research (BMBF).

SECURE ENCRYPTION IN THE QUANTUM AGE

Asymmetric encryption methods are now common and considered secure. In a few years, quantum computers may render them insecure. Two options can help avoid this nightmare scenario: quantum key distribution (QKD) and post-quantum cryptography (PQC).

Protecting data exchanges nowadays involves a combination of symmetric and asymmetric encryption. In symmetric encryption, the receiver decrypts the data with the same key that the sender used for encryption. The Advanced Encryption Standard (AES) uses this method and was certified by the National Institute of Standards and Technology (NIST) in 2000. It is now used worldwide.

Securing symmetric cryptography – asymmetrically

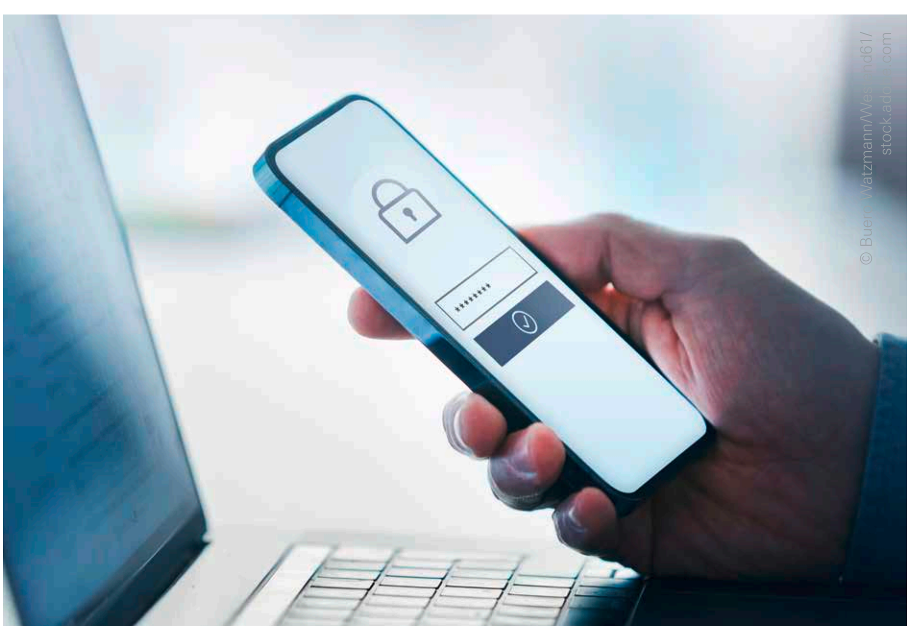
The critical issue in symmetric encryption is the secure distribution of keys between the communicating parties. Asymmetric encryption is normally used to protect key distribution. As the name implies, asymmetric key distribution uses a different key for encryption and decryption. A private key is kept confidential and a public key is provided with certified authenticity. The public key can be transmitted in a public channel without any further protection. An important factor here is that the public key is one way: once data is encrypted, only a private key can decrypt it.

The receiver initiates data transmission in the asymmetric encryption process, generates the public and private key pair and makes the public key available on the key server (Fig. 1). The sender encrypts the message with the public key and transfers it to the receiver. The receiver decrypts it with their private key. The strength of this method is that the sensitive private key remains with the receiver from the start and is not transmitted.

Since asymmetric encryption needs much more computing power than symmetric encryption, it tends not to be used for actual data traffic. Instead, the method secures the key distribution process for the symmetric encryption used for payload traffic.

Mathematical firewall

Since the public key is used for encryption, it also contains certain information about the decryption process. In principle, the private key can be deduced from the public key – but not within a reasonable amount of time. Public keys use mathematical problems that are difficult to solve, such as prime factorization (Fig. 2) or the calculation of discrete logarithms. Deducing the private key would take an impossible amount of time. A conventional computer might need a few million years – or longer – to solve such problems.



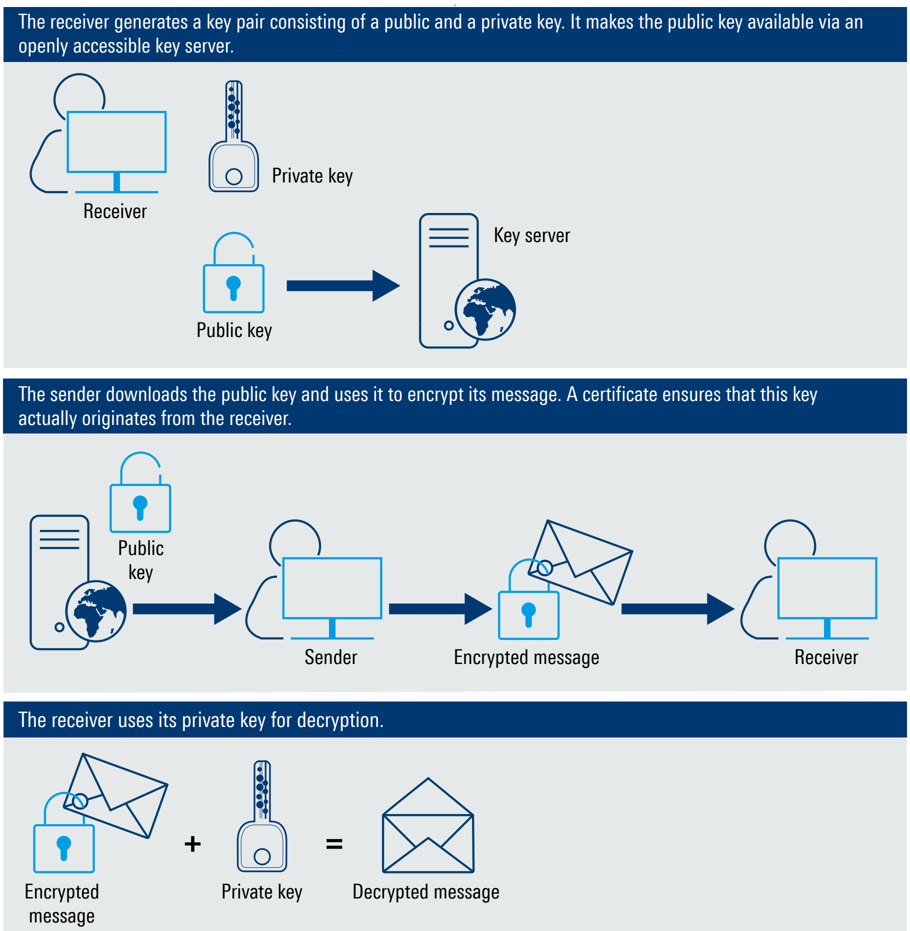


Fig. 1: Basic principle of asymmetric cryptography.

Advanced quantum computers are a game changer

When advanced quantum computers are taken into consideration, the situation changes entirely. Shor's algorithm was published back in 1994. It describes a method that significantly speeds up the factorization of prime numbers and the determination of discrete logarithms. It is a quantum algorithm that requires a quantum computer with sufficient computing power. Since nearly all of the asymmetric cryptographic methods used today are based on these two mathematical problems, advanced quantum computers would rob them of their theoretical foundation. Although quantum algorithms are already known that can directly attack symmetric encryption methods, longer keys can preserve the level of protection here. However, no prior securing of key distribution is possible since the asymmetric encryption methods would be broken.

These encryption methods have not yet been broken. As far as we can tell, no quantum computer currently has enough computing power. However, well-known companies such as Google, IBM and Amazon are working hard on them. Many countries speed up their development with funding for national and international projects. Experts at Germany's Federal Office for Information Security (BSI) anticipate a 20% chance that the first quantum computers will be able to break currently secure encryption methods by 2030. Pressure is mounting to begin encrypting data with quantum-secure methods. This is especially critical for organizations and government authorities that handle larger quantities of sensitive data for extended periods of time. They will need a lot of time to convert the data they manage to quantum-secure encryption.

PQC and QKD: two methods with one goal

We currently have two promising quantum-secure encryption methods. In post-quantum cryptography (PQC), researchers develop special asymmetric algorithms impossible to break within a reasonable amount of time, even with a quantum computer. Some promising candidates are based on diverse mathematical problems such as lattices or cryptographic hash functions. Another PQC approach uses error-correcting codes that a quantum computer supposedly cannot break efficiently.

One major advantage of PQC is that existing network infrastructure can continue to be used. However, certain challenges still remain. Some promising PQC candidates were recently broken. Furthermore, when compared

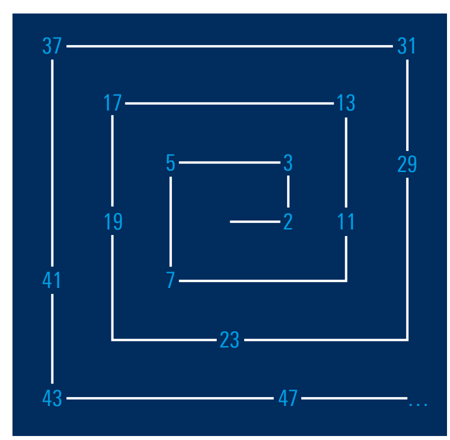


Fig. 2: In the Ulam spiral – named after the Polish mathematician Stanislaw Marcin Ulam – prime numbers often occur on diagonals. While this suggests there might be an underlying system, no method has yet been discovered that can be used to quickly tell whether a large number is prime or not. Accordingly, a very large amount of time is required if, given the product of two large prime numbers $p \cdot q$, we wish to determine the values of the individual factors p and q. The one-way function of the public key in asymmetric encryption methods such as RSA is based on this phenomenon.

to conventional asymmetric methods, PQC has problems with efficiency and key length. A lot of R&D effort is currently focused on these issues.

Quantum key distribution (QKD)

Quantum key distribution (QKD) takes an entirely different approach. Certain fundamental laws of quantum physics are utilized to generate and securely distribute keys which can be used for symmetric cryptography. Instead of conventional bits, the communicating parties exchange qubits that are based on the quantum states of individual photons.

QKD has the advantage that individual quantum states cannot be perfectly copied and any third party trying to measure the photons to get their hands on a key can be discovered. These two fundamental laws of physics can be cleverly utilized to gain an advantage over a potential attacker. If the measured qubits are correctly postprocessed, a bit sequence can be generated that is known only to the two parties and can be used as a key (see article "Quantum key distribution" on page 34). If asymmetric cryptographic methods are broken, QKD can be a very important alternative. Quantum key distribution is based the laws of physics and information theory. The security of a key is independent of the processing power of quantum and conventional computers.

QKD-capable devices and infrastructure

Many QKD protocols are now available. In line with the principles described above, they are based on different degrees of freedom, including polarization as well as time and phase, and require different mechanisms to measure the quantum state. Some protocols are already

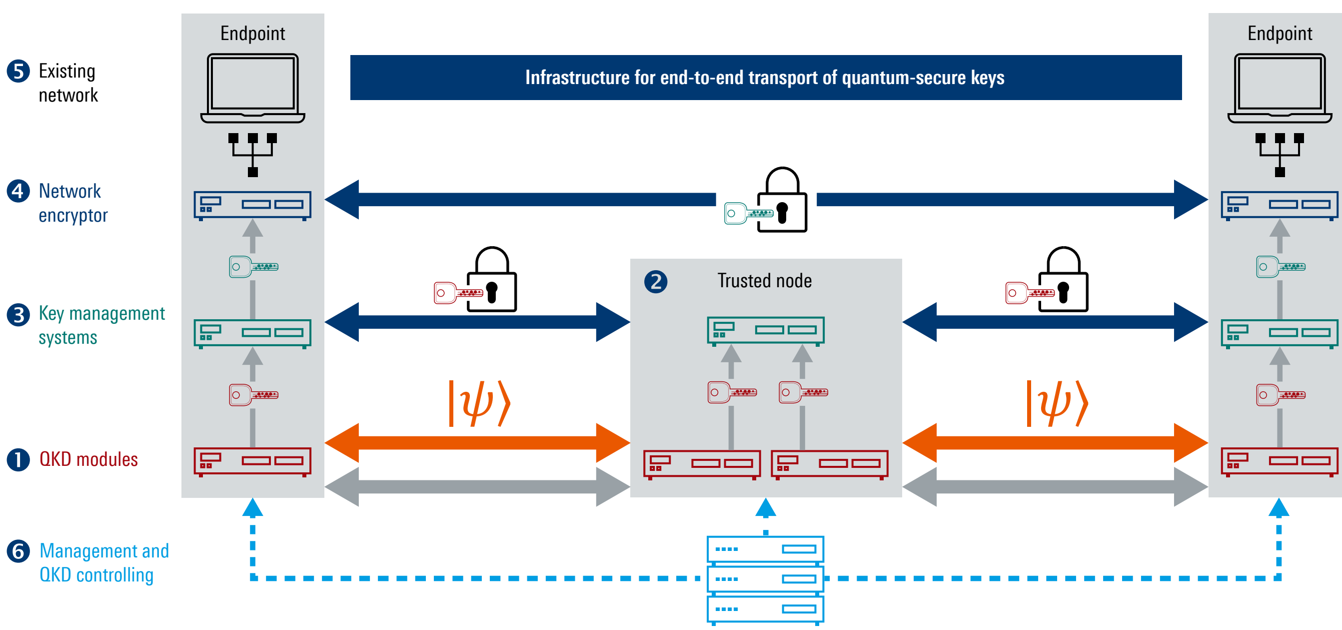


Fig. 3: Multiple elements are required to expand existing networks with QKD: (1) QKD modules to generate the quantum keys, (2) trusted nodes to transmit quantum keys over distances of more than 100 kilometers, (3) key management systems (KMS) to receive, process and manage quantum keys and transfer them to (4) network encryptors for user queries. Network encryptors are the link to existing networks (5) and must have interfaces and functions for receiving quantum keys. Since complex networks consist of multiple individual networks, (6) management and QKD controlling provide cross-network KMS and QKD module management and key transmission routing.

well-developed and used in real applications. The first QKD solutions for secure point-to-point communications can now be purchased from a variety of suppliers. The range of available products will continue to grow in the near future.

Since quantum states cannot be copied perfectly, optical amplifiers cannot be used for long-distance transmission. QKD currently has a range limited to about 100 km. At greater distances, the data rate is too low for practical applications. This also affects network topologies requiring trusted nodes. Moreover, quantum encryption requires additional network infrastructure, beyond existing communications infrastructure, to transmit quantum bits. This infrastructure is currently being implemented in various regions around the world. The procedure is similar everywhere: individual point-to-point links are combined into larger test networks which are increasingly forming a commercially viable network. The largest QKD network is the quantum backbone network. It was officially completed in 2017 and has since been expanded across all of China.

The European Union launched a program known as the European Quantum Communications Infrastructure (EuroQCI) initiative in 2019. Using optical fibers and satellite links, it will span the whole European Union, including overseas territories. The national networks created in this process will combine to form a common European network in the coming years.

Fig. 4: European QKD network
The EuroQCI initiative signals the commitment of the 27 EU member states to create national QKD networks from 2023 onwards. As an example, the networks of a few countries are shown here in different colors. These networks will gradually be brought together to form a common European network by 2027.

QKD network elements

A quantum network is more than just QKD devices. It must also include hardened systems for key management, QKD-capable encryptors and control and management systems. Rohde & Schwarz Cybersecurity GmbH has recently become much more involved in the field. The company is working with various partners to develop functions and products – some of which can already be found in current solutions.

Rohde & Schwarz Cybersecurity has long been a trusted supplier of BSI-approved IT security solutions and can build on existing technology for conventional networks when developing QKD-capable encryptors. The functional range of these encryptors has been extended for use in QKD networks. They have been successfully deployed and are in continuous operation in European test networks as part of research projects. Other technologies such as key management systems are being developed from the ground up. Rohde & Schwarz Cybersecurity expertise with hardened, approved security solutions is a major benefit since these systems need to be hardened for approval as well.

DR. HENNING MAIER, DR. JASPER RÖDIGER, STEFAN RÖHRICH (ALL FROM ROHDE & SCHWARZ)

QUANTUM KEY DISTRIBUTION

Quantum key distribution (QKD) is set to replace asymmetric encryption and support confidential communications – even in the quantum computer era. The technology is already available in some promising early-stage applications.

As the name implies, quantum key distribution (QKD) distributes encryption keys, not actual data traffic. Instead, a secret key is created that other encryption methods can employ to encrypt or authenticate data. QKD keys can be used in efficient and popular symmetric encryption methods. While symmetric encryption is sufficiently protecting against unauthorized decryption with quantum computers, the same cannot be said of asymmetric encryption used to protect symmetric key distribution (see article "Secure encryption in the quantum age" on page 30). QKD has great potential as a quantum-secure replacement for asymmetric cryptographic methods.

The primary objective of QKD is to support secure communications in highly sensitive networks, such as government organizations, critical infrastructure, banks or communications channels between major company sites. The following describes how QKD works in detail.

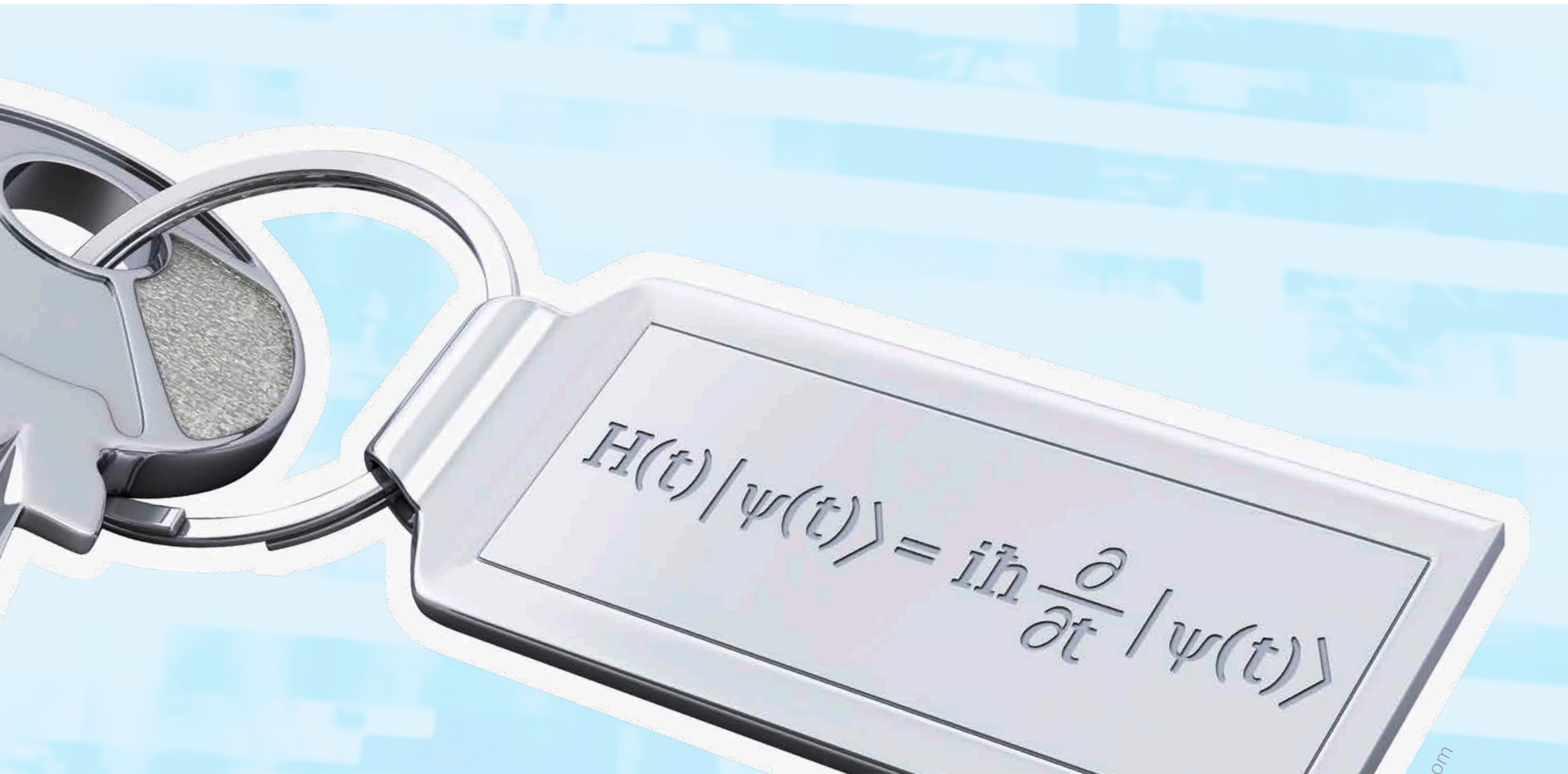
Communicating over two channels

In its basic application, the goal in encryption is to have a common key known only to two endpoints called Alice and Bob. QKD always uses two communications channels. The quantum channel transports a sequence of qubits where some of the qubits – but not all – form the secret key. The transmission uses individual photons commonly transmitted through an optic fiber. The second channel is a conventional communications link that requires authentication. Alice and Bob exchange information via the authenticated channel in multiple rounds to generate a common key from the qubit sequence transmitted in the quantum channel.

In terms of security, it is assumed that an eavesdropper (Eve) can arbitrarily measure and manipulate the quantum channel in line with applicable laws of physics. The authentication means Eve can only listen to the conventional channel but not manipulate it.

The firewall: quantum physics and information theory

QKD security exploits two fundamental physical properties: Heisenberg's uncertainty principle and the no-cloning theorem. Heisenberg's uncertainty principle tells us that certain pairs of measurement quantities cannot be simultaneously measured with high accuracy. The more precise the measurement of one parameter, the greater the imprecision of the other. QKD techniques often use time phase or polarization uncertainty relationships of individual photons. The no-cloning theorem tells us that qubits cannot be perfectly copied and any eavesdropping on the quantum channel always leaves detectable traces.



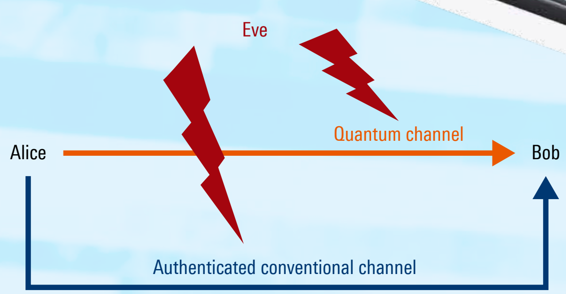


Fig. 1: Quantum key distribution requires two communications channels. This method takes into account that both channels can be eavesdropped and that the quantum channel can also be manipulated.

How QKD works

The BB84 protocol clearly illustrates the underlying QKD principle. Historically, it was the first QKD protocol and was proposed by Charles H. Bennett and Gilles Brassard in 1984 and is thus called BB84. Its basic principles can be transferred to other QKD protocols.

The BB84 protocol gives Alice (the sender) and Bob (the receiver) an information advantage over Eve (the eavesdropper) by cleverly exploiting Heisenberg's uncertainty principle and the no-cloning theorem in the transmission of quantum bits. This information advantage shows itself in the postprocessing of the qubit sequence. Upon completion of the error estimation, error correction and privacy amplification, Alice and Bob will have a common and secure key available only to them. The following takes a detailed look at the three steps of the encryption process.

Communications starts via the quantum channel. Alice sends a sequence of qubits with encoded photons that use different linear polarizations. Bob measures the polarization of the received photons. They define two coding bases that are rotated relative to one another (Fig. 2).

Heisenberg's uncertainty principle states that Bob will measure the correct polarization of a received photon only by using the same basis that Alice used to send it. If Bob chooses the wrong base, the result will be random and statistically correct about 50 % of the time. For each qubit sent, Alice and Bob select one of the two bases randomly and independently of one another. Although this might appear unnecessarily complex at first, it is an effective protective mechanism. After sending a longer qubit sequence, Alice and Bob inform one another about their choice of bases in an authenticated standard channel – but they say nothing about the actual bits sent. They discard all measurements where their bases differ (sifting process). Since Eve must also randomly choose bases to eavesdrop on communications, it is practically impossible to always make the right choice. The resulting errors are passed along from Eve to Bob. The more photons Eve tries to eavesdrop on, the more errors she generates.

Postprocessing: three steps to a secure quantum key

Alice and Bob can exploit these errors in postprocessing. They compare a small sample of randomly chosen bit values for error estimation. Since eavesdropping is possible here, Alice and Bob will discard these bits. This small set of bit values can be used to estimate an error rate for the complete qubit sequence and determine the maximum amount of information that Eve could have obtained about the key. In information theory, this describes the mutual information between the sender and receiver about the qubit sequence. Fig. 3 shows the relationship between the error rate and mutual information.

The amount of mutual information between Alice and Bob decreases in proportion to the number of errors in a transmission. Due to the polarization uncertainty principle along with the selection of the two bases, Eve's actions create transmission errors. When the error rate increases, Eve's maximum potential mutual information with Alice increases, i.e. Eve's knowledge about the key. Although errors are possible in real-world applications from interference such as line noise, the security assessment requires assuming the worst case where all errors result from eavesdropping by Eve. The error rate provides a direct indication of the maximum amount of information about the qubit sequence that Eve could determine. When a certain error threshold is exceeded, the key exchange must be interrupted and restarted from the beginning. Eve will not be able to conceal the error rate increase by making measurements with perfect copies of the intercepted qubits while forwarding error-free originals along to Bob. The no-cloning theorem prevents precisely this sort of attack.

As long as Alice and Bob are to the left of where the lines intersect in Fig. 3, they have an information advantage and can generate a common key unknown to Eve. Two more steps are still needed.

During error correction, the remaining errors are eliminated between the bit sequences of Alice and Bob. This involves exchanging additional qubits in the sequence through the authenticated channel. The two qubit sequences must match (Fig. 4). The mutual information transmitted per

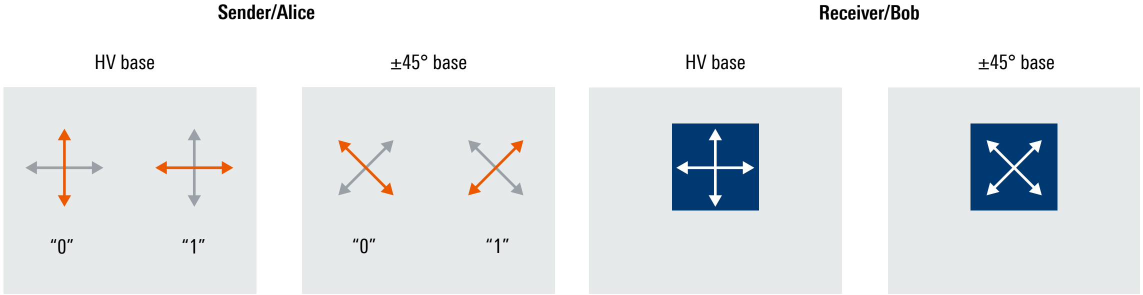


Fig. 2: In the horizontal-vertical base (HV), vertical polarization represents a bit value of zero and horizontal polarization a bit value of one. This applies analogously in the rotated 45° base.

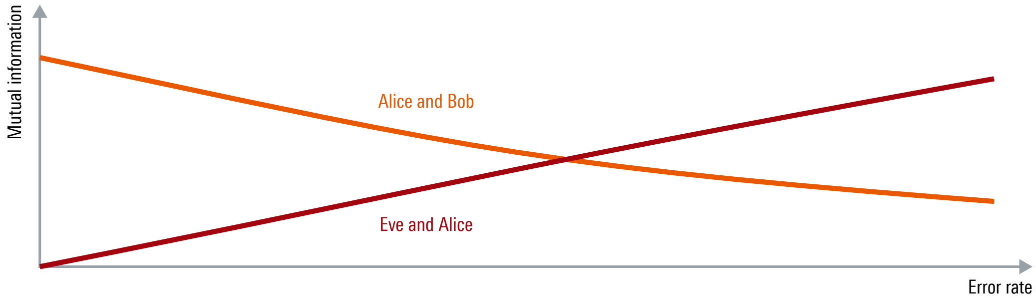


Fig. 3: Eavesdropping on the quantum channel causes transmission errors. At the point of intersection, sender Alice and receiver Bob have exactly as much mutual information about the qubit sequence as sender Alice and eavesdropper Eve.

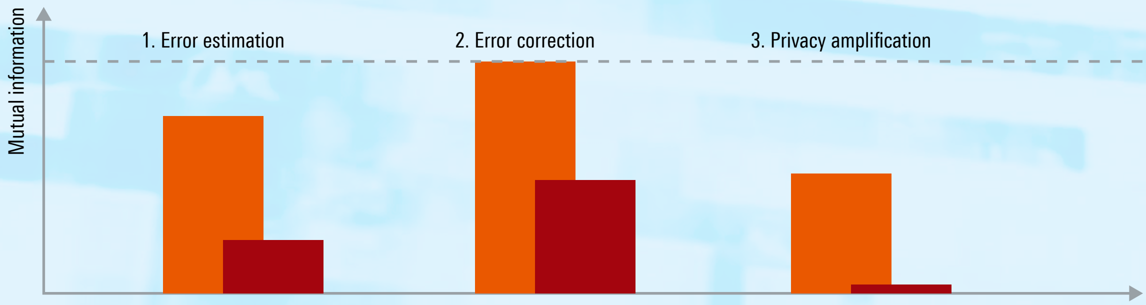


Fig. 4: The mutual information about the bit sequence between Alice and Bob (orange) changes over the course of the three postprocessing steps. The mutual information between Alice and Eve (red) is minimized at the end. The dashed horizontal line represents the threshold where the mutual information per bit is equal to a value of one. The red bar that remains after privacy amplification is only shown symbolically.

qubit is equal to one. However, since Eve might be eavesdropping, Eve also obtains certain information about the key. The orange and red bars increase in this step.

The third step uses the authenticated conventional channel. Alice and Bob can minimize Eve's knowledge about their common key by using functions that take a larger number of bits as input and generate output with fewer bits. The resulting bits can be calculated only if all of the input bits are known. This is only true for Alice and Bob after error correction. They now have a bit sequence that is fully unknown to Eve. This is the secret key. Although this final step does not increase the information difference, it makes sense from a security perspective to not provide any information at all to potential attackers about the key.

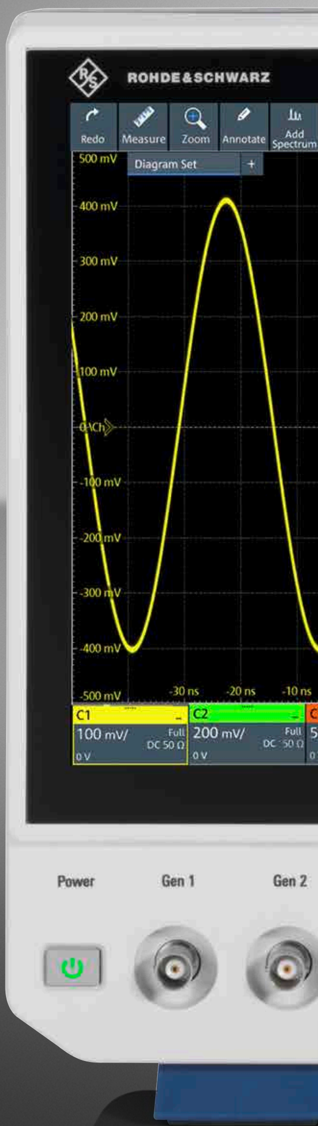
DR. JASPER RÖDIGER, ROHDE & SCHWARZ

QKD AT ROHDE & SCHWARZ

The European Telecommunications Standards Institute (ETSI) has specified the ETSI GS QKD 004 and ETSI GS QKD 014 standards for multivendor compatibility between QKD-capable devices.

The R&S®SITLine ETH Ethernet encryptors have been extended to include an interface complying with these standards. They are intended for connection to QKD modules. The company portfolio will be expanded step by step in the coming years to include a variety of secure, QKD-capable network equipment.

Fig. 5: The R&S®SITLine ETH-XL Ethernet encryptor is QKD-ready.



NEW MIDRANGE BENCHMARKS

The R&S®MXO 4 oscilloscopes have digital triggering, extremely fast update rates and a brand new ASIC to beef up midrange products with many functions.

After entering the oscilloscope market in 2010, Rohde & Schwarz quickly built up a broad product portfolio. Now covering bandwidths from 70 MHz to 16 GHz, the portfolio ranges from handheld oscilloscopes for field use and entry-level models for educational applications up to high-end instruments for R&D labs. Innovation is typically exclusive to higher-performance instruments. However, this does not apply to the latest series of R&S®MXO 4 oscilloscopes. They offer the performance of top-class instruments – including a number of pioneering functions – at a price that puts them clearly in the midrange segment. The new instrument family comes in four-channel models with bandwidths of 200 MHz to 1.5 GHz.

Instant view of signal details

The real-time update rate of over 4.5 million waveforms per second is a new milestone for the oscilloscope market. High update rates increase the likelihood of detecting very fast signals that occur at irregular intervals (Fig. 1), giving developers a better understanding of their designs and shortening testing times.

Signal processing is handled by the MXO-EP, a 200 Gbit/s ASIC developed internally by company engineers (Fig. 3). It is one of several new technology blocks in the R&S®MXO 4. The oscilloscope maintains a fast update rate even when complex functions are active, such as automated measurements, spectrum analysis or deep memory acquisitions. Customized ASIC signal processing ensures smooth workflows.

Uncompromising 12-bit resolution

A 12-bit ADC converts the input signal to a digital signal. It operates across all sample rates without any tradeoffs. Compared to the traditional 8-bit architecture in many oscilloscopes, it represents a 16-fold improvement in vertical resolution. The HD mode achieves up to 18-bit vertical resolution, allowing users to see signal details that would otherwise be masked by noise. The HD mode is implemented directly in hardware for the sake of speed. The R&S®MXO 4 also sets a new benchmark for noise with only 22 µV AC (RMS) at 1 mV/div.

It offers outstanding sensitivity down to 500 µV/div without any unexpected reduction in bandwidth along with the largest offset range of ±5 V with a 500 µV/div scaling on a 50 Ω path without any special probes. Users can easily place waveforms at the center of the screen for straightforward analysis, especially in case of signals with significant DC components.

Capture more time

Standard acquisition memory of 400 Mpts is simultaneously available on all four channels – with no extensions needed. The memory depth far exceeds typical base configurations by the competition. Users can capture more time and utilize the full instrument bandwidth, even with slower timebase settings.

The segmented memory helps efficiently capture signals of interest and ignore periods of inactivity. When analyzing laser signals, streams of

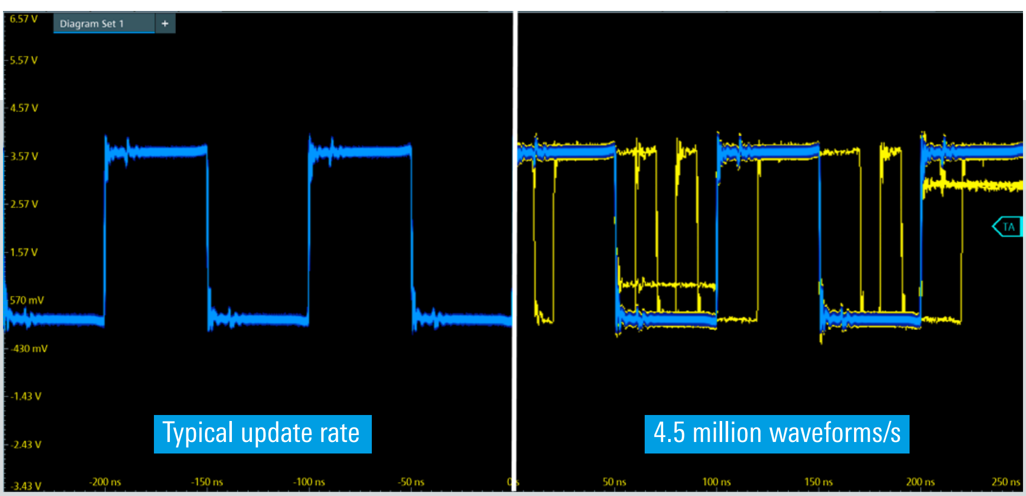


Fig. 1: An update rate of 4.5 million waveforms per second helps detect signals that could be missed otherwise.

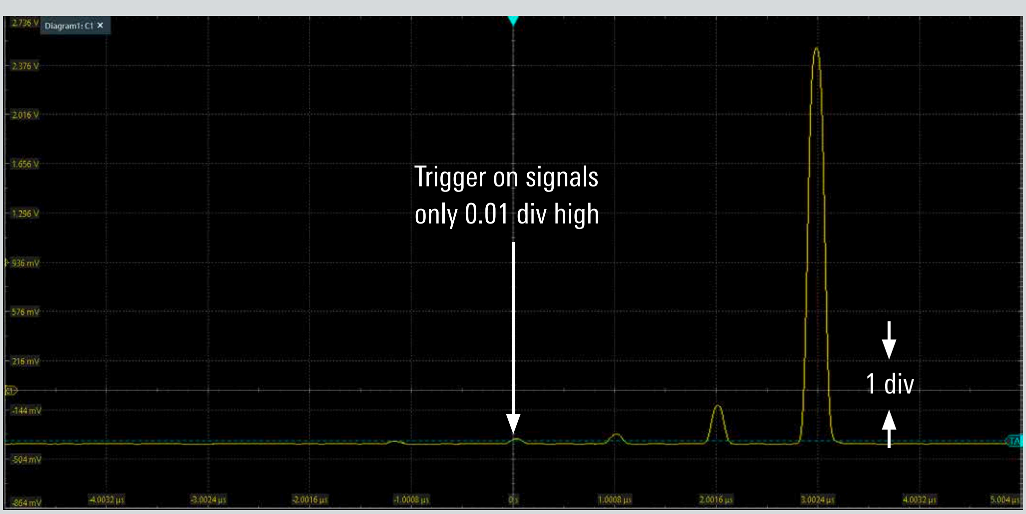


Fig. 2: The R&S®MXO 4 offers the industry's most sensitive trigger of 1/10 000 vertical division and maintains a very short trigger rearm time of < 21 ns.

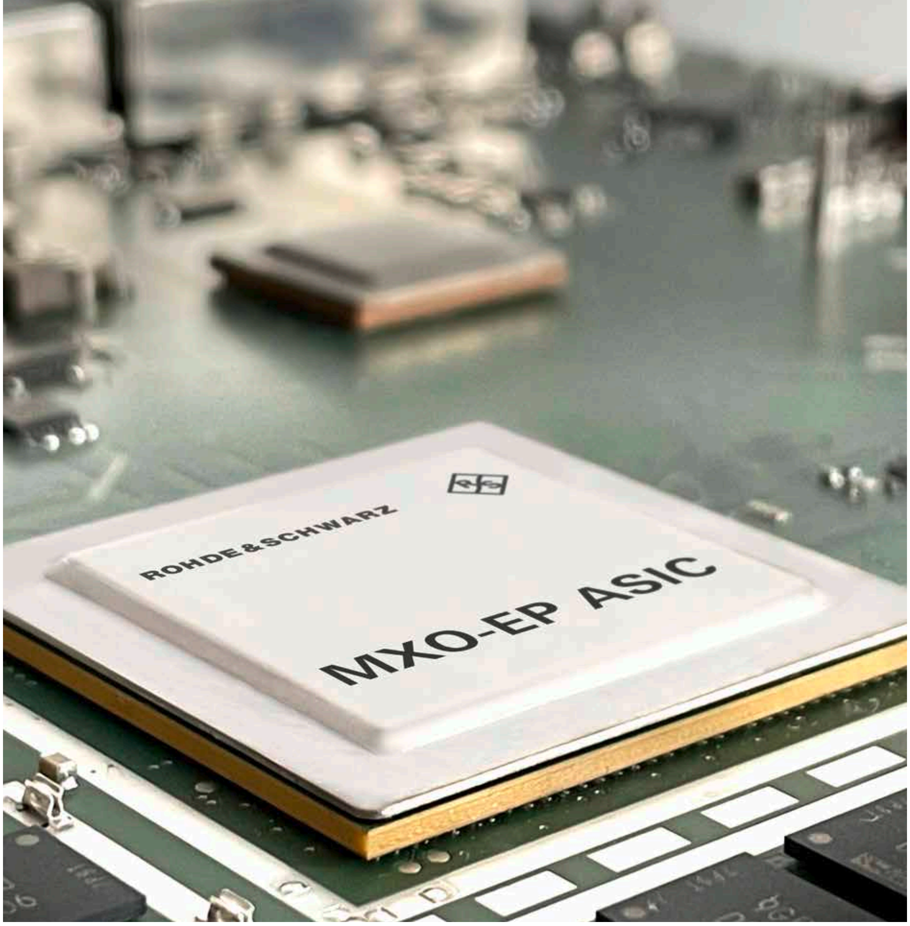


Fig. 3: A new 200 Gbit/s ASIC inside the R&S®MXO 4 was custom-developed for signal processing.

serial bus activity or RF pulses, the active signal transmission phases can be precisely targeted. Periods of inactivity are irrelevant. They can be ignored with the segmented memory and are not recorded at all. Segmented memory is a standard R&S®MXO 4 feature. More memory leaves users flexible to capture longer signals or to select a wider bandwidth. The oscilloscope series has a history mode that captures the signal at all times and does not have to be manually activated. Users can dial back to see previous acquisitions or segments. An optional memory extension up to 800 Mpts is ideal for analyzing the power up/down behavior of components.

High-precision digital trigger

Nearly all scopes in the market have analog triggers. The measured signal is split into one path for viewing the signal and another path for triggering. The analog approach does not allow users to trigger on small signal changes and the filters that can be applied to the trigger signal are limited. Rohde & Schwarz made triggering digital with a single signal path that encompasses both trigger and signal visualization. In high-priced, high-performance oscilloscopes, digital triggering has already proved to be significantly more precise and sensitive than analog triggering. It offers new possibilities for triggering on extremely fine signal details (Fig. 2) and can be combined with a larger number of filters.

Previously reserved for the upper class, this function is now included as standard in the R&S®MXO 4 oscilloscopes. No competitive oscilloscope has this high degree of trigger sensitivity. Full access to control all trigger hysteresis settings provides greater flexibility for determining where to trigger, including how much trigger noise suppression is needed. In combination with their 12-bit architecture and HD mode, these instruments offer everything users expect from a state-of-the-art oscilloscope in terms of measurement precision and even more.

Powerful frequency domain

Oscilloscopes are time-domain instruments. However, because product developers need to perform measurements in the frequency domain as well, the R&S®MXO 4 oscilloscopes have high-performance spectrum analysis functions. They are the first oscilloscopes ever to achieve 45 000 fast Fourier transforms (FFT) per second. Comparable oscilloscopes deliver less than 10 FFTs per second. This makes it possible to quickly and easily capture spurious spectrum events, especially when debugging EMI problems (Fig. 4).

Configuring the spectrum function has been made simple by entering common parameters such as center frequency, span and resolution bandwidth (RBW). These settings are independent of the time-domain settings but still time-correlated. The synchronized view of the signal spectrum is preserved. Spectrum analysis functions are included in the base instrument, allowing product developers better visibility of RF signals than with any other oscilloscope in its class.

Incorporating user feedback

Using an oscilloscope is a visual experience and users spend significant time interacting with the instrument display. The R&S®MXO 4 series features a 13.3" full-HD capacitive touchscreen with gesture support. Extensive user feedback went into the development of the intuitive user interface (Fig. 5). Its straightforward box design provides enhanced usability by allowing users to touch any part of the setting field to change parameters. Larger touchscreen buttons make it easy to work effectively. Alternatively, a mouse and/or keyboard can be used. The efficiently organized toolbar provides quick access to important and popular functions with a single gesture. When the standard display is insufficient for the measurement at hand, R&S®SmartGrid lets users set an individual waveform layout to keep an eye on important details. R&S®SmartGrid is another function that was previously only available in higher performance oscilloscopes.

Beyond the base unit

The instrument's small footprint, low audible noise, VESA mounting and a rackmount kit for installation in integrated environments make the R&S®MXO 4 oscilloscope ideal for different workstations.

JITHU ABRAHAM, ROHDE & SCHWARZ

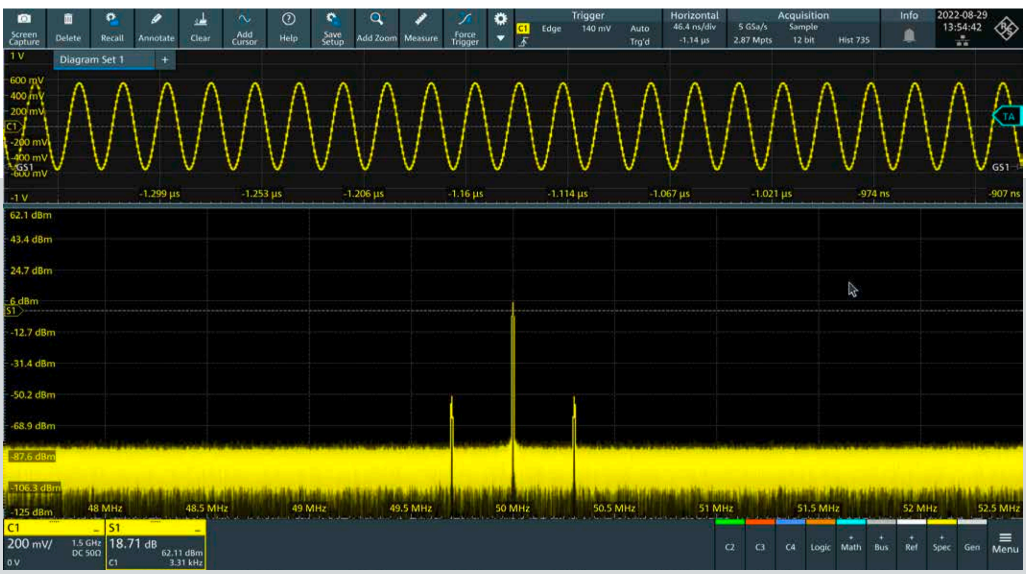


Fig. 4: The R&S®MXO 4 spectrum function offers the familiar interface of a spectrum analyzer.

Fig. 5: Waveform viewing is maximized even when setting dialogs are open. This fulfills a key user requirement.

A number of upgrade options are available, including a mixed signal oscilloscope (MSO) option with 16 integrated digital channels, an integrated dual-channel 100 MHz arbitrary generator as well as protocol decode and triggering options for a variety of industry standard buses. Dedicated probes for power measurements include active and passive probes for voltage and current ranges from µA to kA and from µV to kV. Special power rail probes detect even small and sporadic distortions on DC power rails.

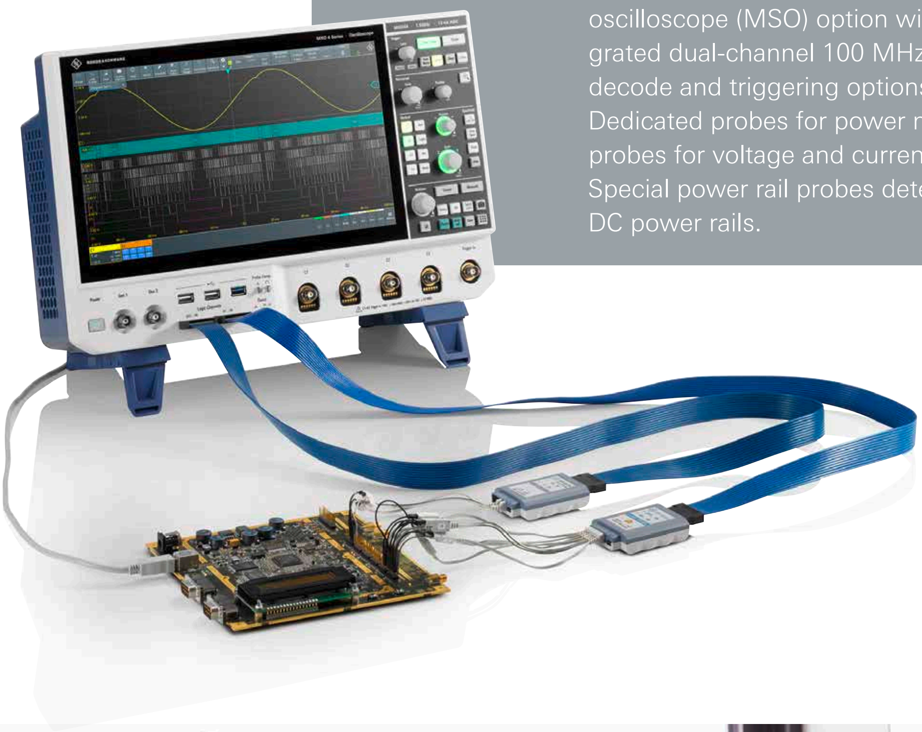


Fig. 6: The new R&S®MXO 4 oscilloscope with mixed signal option (MSO) and DUT.

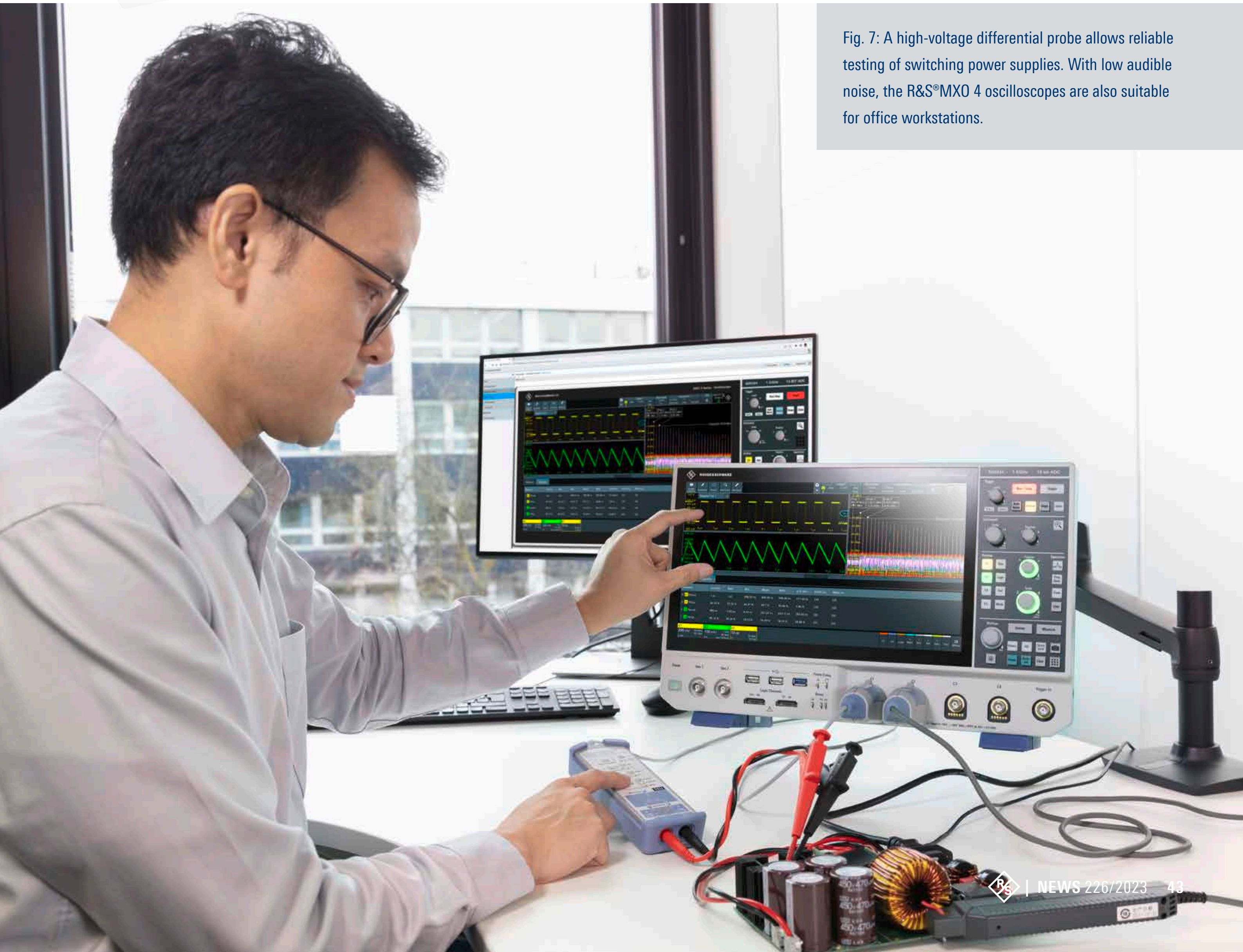


Fig. 7: A high-voltage differential probe allows reliable testing of switching power supplies. With low audible noise, the R&S®MXO 4 oscilloscopes are also suitable for office workstations.

EYES WIDE OPEN FOR SIGNAL INTEGRITY

Eye diagrams are very practical for signal integrity tests. For the first time, the R&S®RTP oscilloscope uses a hardware based approach to calculate eye diagrams for quick serial signal analysis.

Eye diagrams give a quick overview of data signal jitter and noise while also revealing the robustness of data transmissions. Numerous fast bus interface standards, such as USB and PCI Express (PCIe), now define eye masks for signal integrity testing, clearly illustrating their importance.

Eye diagrams for serial and parallel data transmission

Reliable analysis requires superimposing large numbers of data bits to form an eye diagram. However, a bit based time reference is needed to extract the individual bits from a data stream. The time reference can be in the form of a second signal (clock or data strobe) as seen in parallel DDR interfaces. Serial signals have the clock signal embedded in the data stream. The clock signal must therefore first be recovered using clock data recovery (CDR). Then the oscilloscope can use it as a reference for displaying the eye diagram. This step usually involves software based postprocessing of the data signal and demands a certain amount of computation time. The final eye diagram reveals signal quality by the height and width of the eye opening, time and amplitude errors in the form of jitter and noise, or predistortion effects.

Much faster with hardware clock data recovery (HW CDR)

Hardware clock data recovery developed by Rohde & Schwarz is now available for the first time in the R&S®RTP high-performance oscilloscopes. Direct integration into the trigger hardware eliminates the need for software computation and saves lots of time. This is an entirely new approach to eye diagram analysis for serial signals.

Users can choose any R&S®RTP input channel as HW CDR source for data rates up to 16 Gbit/s and can set a tracking bandwidth between 1/500 and 1/3000 of the nominal bit rate. HW CDR runs continuously once it successfully locks in on the DUT signal. Timestamps are stored in acquisition memory in parallel with the waveforms and are available for mathematical analysis and eye diagram calculations.

Real-time eye diagrams for long-term observation

Triggering with HW CDR enables eye diagram analysis in near real time. The oscilloscope simply acquires short signal sequences and displays them immediately in the diagram. When the persistence is set to infinite, the eye diagram will form quickly. The R&S®RTP can reach a maximum rate here of over 400 000 unit intervals (nominal bit width) per second. This means sporadic errors, such as crosstalk between adjacent components, are detected quickly and reliably. Mask tests and histograms enable further analysis without significantly slowing the acquisition rate. This also includes long-term observations, where mask test errors can stop measurements to track down error sources. The high HW CDR acquisition rate ensures that fast and sporadic signals are not missed, even with long observation times.

Standard-specific eye diagram analysis of a long data stream

R&S®RTP HW CDR also enables eye diagram analysis for long contiguous bitstreams, as required, for example, in compliance with the test specifications for the USB or PCIe standard. Along with the actual waveforms, it stores HW CDR edge times and makes them available for fast eye diagram calculation.

The eye diagram function also makes other settings for computation and visualization possible. For example, users can display an eye diagram for only those bits preceded by a bit change or by a user-defined bit sequence.

From quick start to detailed analysis

Users can carry out further detailed analyses once the eye diagram is displayed. Along with simple cursor measurements, the oscilloscope has a broad range of automated eye diagram measurements.

Eye mask testing is another important function. Signals passing through a mask are registered as violations. The R&S®RTP oscilloscope provides predefined masks for many standards. But users can also quickly create other masks, either directly on the screen or using specific settings in the mask dialog.

The eye stripe function marks a violation of the eye mask as a red stripe at the corresponding time point in the original waveform. This makes it easier to identify the causes of mask violations. When zoom coupling is enabled, the waveform zoom function focuses on the violation selected in the current result table.

The bit transitions at the left and right of the eye diagram show signal jitter while the signal amplitudes in the center of the eye diagram show signal noise. The histogram function makes it quick and easy to see the distribution of jitter and noise. Users can also break down the individual components even further using the R&S®RTP-K134 jitter and noise decomposition option.

Summary

The R&S®RTP high-performance oscilloscope offers a broad range of comprehensive features for analyzing the signal integrity of electrical signals. Integrated HW CDR triggering is available for the first time thanks to the R&S®RTP-K137 advanced eye analysis option, which supports data rates up to 16 Gbit/s. This allows users to quickly record short bit sequences for fast eye diagrams and to analyze long bit sequences in compliance with test standards.

GUIDO SCHULZE, ROHDE & SCHWARZ

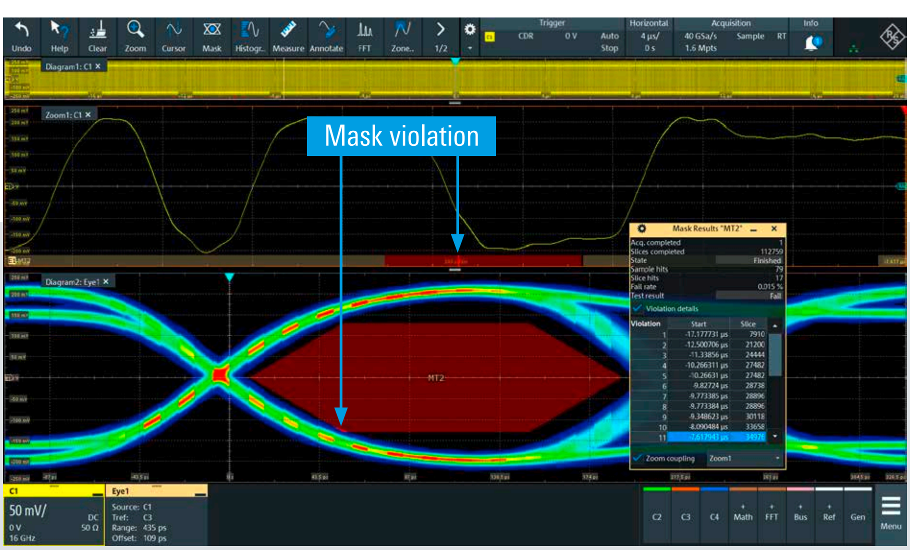


Fig. 1: The eye stripe function makes debugging much easier. Mask violations are marked in red in the eye diagram and in the time signal of the waveform (blue arrows). All violations are listed in the results table and the currently displayed signal section is marked in blue.

PRECISE IMPEDANCE CHARACTERIZATION

Measuring the impedance of passive components is relevant for both electronics developers and component manufacturers. The R&S®LCX LCR meters generate test signals of up to 10 MHz and offer customized measurement functions for transformers.

With the R&S®LCX family of LCR meters, Rohde & Schwarz is entering the market for high-accuracy impedance measurements.

Designers of galvanically isolated switched-mode power supplies (SMPS) need suitable high frequency transformers. Customizing a design is always a tradeoff. Greater magnetizing inductance tends to increase leakage inductance and leakage flux, especially when different forms of isolation barriers are planned between the primary and secondary winding. This may cause increased power losses in the transformer and electromagnetic compatibility (EMC) problems from increased interference emissions, especially at higher converter switching frequencies.

Characterize transformers quickly

Transformers need to be precisely characterized to estimate their impact on the efficiency, maximum voltage and EMC behavior of switching elements. Besides leakage inductance, other parameters such as primary and secondary inductance, winding capacitance and winding resistance are relevant and necessary for high-quality circuit designs.

The R&S®LCX LCR meters are ideal for these tasks. They also provide other transformer-specific parameters that users would have to calculate themselves, such as mutual inductance and turns ratio.

Two models cover basic and advanced measurement requirements

The LCR meters were developed to precisely measure all standard passive components using the auto-balancing bridge method. The instruments have a user-friendly 5" color LCD touchscreen. Extensive remote control functions enable use in automated systems and operation via a web interface.

The instruments come in two models, providing all the modern measurement functions needed in R&D and production. The R&S®LCX100 has a test signal frequency range from 4 Hz to 300 kHz for basic lab applications. The base configuration of the R&S®LCX200 has an upper frequency limit of 500 kHz that can be extended to 1 MHz or 10 MHz to determine the self-resonance frequency of components. Both instruments have an impedance measurement range from 10 mΩ to 100 MΩ and a basic impedance measurement accuracy of ±0.05 %. Comprehensive analysis functions and versatile selection of test fixtures enable the meters to measure a broad range of components.

Fully automated component sorting

The LCR meters open the door to process automation. The R&S®LCX-K107 option expands the meter interfaces with a digital I/O port that includes a trigger input and eight data lines. This allows components to be sorted in up to eight classes (binning) based on their measurement

ACCESSORIES

R&S®LCX-Z1
test fixture for axial/radial lead type devices

R&S®LCX-Z2
Kelvin clip lead

R&S®LCX-Z3
test fixture for SMD components

R&S®LCX-Z11
BNC extension

R&S®LCX-Z4
test tweezers for SMD components

R&S®LCX-Z5
transformer test cables

values. One criterion could be tolerance values that separate high-precision capacitors from standard ones. Together with a handling robot that inserts the components into test fixtures, the LCR meter helps automate component production. As part of larger test systems, the instruments can be installed in 19" racks using the R&S®ZZA-GE23 rack adapter. The standard logging function records ten measurement values per second and transfers them to the instrument memory, a USB flash drive or to an external PC via a LAN, USB or optional GPIB interface. The fast (≤ 15 ms), medium (≤ 100 ms) and slow (≤ 500 ms) measurement times allow flexibility. Users can determine the best trade-off between required measurement accuracy and available test speed.

Advanced analysis functions

An LCR meter is mostly used for measuring the impedance of components at a fixed frequency and level. However, impedance can vary depending on the DUT, making it necessary to perform measurements at various frequencies and levels. The R&S®LCX-K106 option can perform local dynamic impedance measurements, where test signals with different frequencies are generated. The R&S®LCX sweep tool can also be embedded. The software runs on an external measurement PC and enables sweep measurements with an R&S®LCX LCR meter. The frequency or level of the test signal or the DC bias voltage can be selected as sweep parameters. The tool plots the measurement results in tables or graphs, such as a Nyquist diagram.

The LCR meters generate test signals from 100 mV to 10 V and DC bias signals up to 10 V and up to 40 V with the R&S®LCX-K108 option using an external source.

Summary

The R&S®LCX LCR meters precisely measure the impedance characteristics of passive components such as capacitors, inductors, resistors and transformers. The R&S®LCX100 and R&S®LCX200 comply with all standard requirements for high-end research and production applications and component testing in the lab. Numerous measurement and analysis functions along with user friendliness make them unique. The LCR meters measure various transformer properties for high-quality customized transformer designs.

SHIVAM ARORA

Main features of the R&S®LCX LCR meters

	R&S®LCX100	R&S®LCX200
Impedance measurement range	10 mΩ to 100 MΩ	
Basic accuracy for impedance measurements	±0.05%	
Internal bias voltage	0 V to 10 V (DC)	
Internal bias current (optional)	0 mA to 200 mA (DC)	
External bias voltage (optional)	0 V to 40 V (DC)	
Test signal frequency	DC, 4 Hz to 300 kHz	DC, 4 Hz to 500 kHz (options up to 1 MHz and 10 MHz)
Test signal voltage	100 mV to 10 V	≤ 1 MHz: 100 mV to 10 V, ≤ 5 MHz: 100 mV to 2 V, > 5 MHz: 100 mV to 1 V

6G EVERYTHING WILL BE CONNECTED

Even though 5G networks are expected to grow and develop for years to come, technology strategists are already offering up visions that look far beyond 5G. If their 6G scenarios become reality, we can expect a wonderland of communications in the 2030s.

The LTE standard (4G) meets the needs of most mobile network users. Download speeds of up to several hundred megabits per second make it easy to stream high-resolution video content or download large files within seconds. Already available countrywide in many places, 5G is multiplying the available speed, but it has practically no real benefit for individual users. Nevertheless, research into the next generation of mobile communications has already started and 6G is expected to be rolled out by 2030. But are any needs left unsatisfied by the technically advanced 5G system, which is subject to ongoing development and extension? A pair of authors posed this very question back in September 2018 [1]. What started as a discussion among experts has since gained serious momentum. Political and industrial interest in 6G has triggered a global technological race with billions flowing into research and development.

What needs can 6G meet?

"6G will satisfy the expectations that 5G has created," was how Dr. Dr. Ivan Ndip from the Fraunhofer Institute for Reliability and Microintegration (IZM) pithily described the situation in an interview in spring 2021. Although 5G has yet to reach its full potential, applications are emerging that require 6G for large-scale implementation. Autonomous driving is one example.

At autonomy level 5, which is still a long way off, vehicles will not be as autonomous as the name suggests. After all, vehicles share roads, traffic lights and other infrastructure with countless other road users. For everything to run smoothly, autonomous vehicles must be connected in three ways: with each other, with roadside facilities and with a traffic control center. Since many situations are safety-critical, such as emergency braking, high transmission speeds and reliable signal transfer are vital.

KPI	5G	6G
Peak data rate	20 Gbit/s	1 Tbit/s
Average available data rate	100 Mbit/s	1 Gbit/s
Signal latency	1 ms	0.1 ms
Maximum channel bandwidth	100 MHz	1 GHz
Reliability (error-free data blocks)	99.999 %	99.99999 %
Maximum user density	10^6/km^2	10^7/km^2
Maximum user speed	500 km/h	1000 km/h
Positioning accuracy	20 cm to several meters in 2D	1 cm in 3D

Table 1: Comparison of 5G performance data and KPIs discussed for 6G.

Vehicles require extremely high data rates to exchange sensor data and download detailed traffic plans. 5G is clearly a big step forward, but with a maximum data rate of 20 gigabits per second and signal latency of a millisecond, it is probably not good enough for true autonomous driving. Completely autonomous vehicles will only be possible with 6G, which is to reduce signal latency by a factor of ten and increase data throughput by a factor of fifty (Table 1).

The same is true for telemedicine, especially telesurgery. Surgeons can perform certain remote operations with a 5G data link. In extreme cases, patients and surgeons are even on different continents. Visual data and control commands for the surgical robot must be generated and transferred with little or no latency. Displayed on an ultra high definition screen, visual data allows the surgeon to monitor the surgical area. But complicated operations can test the limits of 5G, and implementing 5G-Advanced in 2024 will not solve the problem.

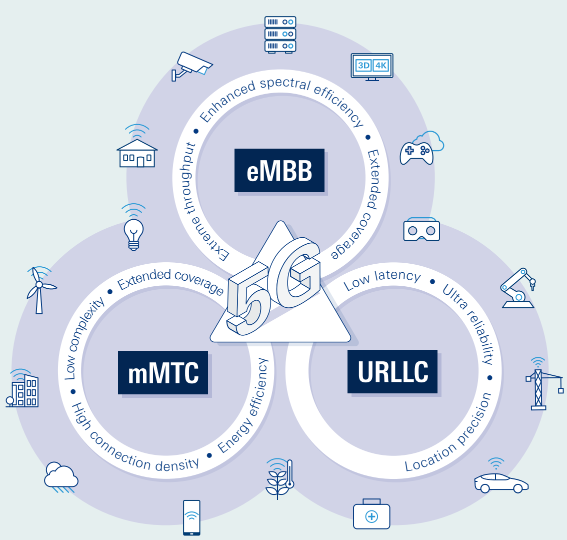


Fig. 1: 5G aims to cover three application groups. Enhanced mobile broadband (eMBB) allows classic mobile applications but with much better performance than LTE. Massive machine type communications (mMTC) supports energy efficient low-performance applications such as sensor networks. Ultra-reliable, low latency communications (URLLC) focuses on real-time applications that require ensured signal transit times and availability.

Autonomous driving, telemedicine and similar scenarios are the forces behind R&D into the next generation of mobile communications.

Focus shifts to machines

In 6G, functions and services for efficient machine-to-machine communications (M2M) will play a vital role.

URLLC and mMTC (see Fig. 1) are two of three key 5G focal points in this area. In addition to autonomous driving, 5G applications include Industry 4.0, smart cities and smart homes. Rather than a single type of M2M communications, many different types are needed. Just look at a connected factory where highly reliable radio links with end-to-end signal transit times in the lower millisecond range are needed. Smart cities or smart homes have completely different requirements. A smart home needs utility meters, sensors and control elements for everyday items such as waste bins or appliances to remotely provide information or automate processes.

These applications only require sporadic radiocommunications with small amounts of data. The radio network for a smart city must connect hundreds or even thousands of identical endpoint devices, many of them battery powered. Such applications were inconceivable when mobile communications were first developed

Fig. 2: Augmented reality glasses are already merging real and virtual worlds, but the vision with 6G is to include all senses for total immersion.

but now define the 5G concept. The main focus has shifted from people to devices or machines and the internet of things (IoT).

The 6G vision

Technical development is closely aligned with the demands of different industries. The visions for 6G vary widely and merge to form a fascinating landscape. Bringing this landscape to life will require technologies that are mostly not yet available, but which are within reach on the medium term. The interaction between all these technologies will create the sixth mobile communications generation, but the term fails to describe the true potential of 6G.

Digital twins on the holodeck

Facebook founder Mark Zuckerberg announced the metaverse in fall 2021 and also changed the company name to Meta. With that he gave once gimmicky VR headsets new market relevance. They are the main tool for implementing Zuckerberg's vision of extended reality. The company has the means, since VR headset manufacturer Oculus is part of the Meta empire.

Reimagining the original idea behind the VR headset is ambitious and visionary. Specialists use the glasses, for example, to project a 3D model of a part to be mounted into the real image – together with information on how to handle the part.

The person wearing the glasses can even interact manually with the holographic projection as if it were real. This includes touching and manipulating the projection. Making such a system available in the millions and affordable for everyone is Zuckerberg's vision and one of the guiding scenarios for 6G.

Extended reality – the combination of real and virtual worlds – encompasses a number of other substantial visions if taken to its logical conclusion. Ultimately, the long-term goal is total immersion into a new world that is experienced as if it were real. This includes elements such as three-dimensional optical resolution capable of fully stimulating human eyesight, an appropriate acoustic environment, instantaneous reaction by all synthetic objects (tactile internet) and finally, a credible representation of all of these things. Some of these objects have to match up with twins in the real world. The digital twin is an interactive, virtual representation of a real object or machine that can be manipulated from the metaworld. The ability to operate machines from practically anywhere has potentially far-reaching consequences for the work environment and society at large. One potential impact is the revival of rural areas, since people will no longer need to move to urban areas for work.

When thinking about scenarios like this, you simply cannot ignore 6G. VR headsets do not have the processing power required for the immersive artificial world of the metaverse. And if we want the headset to be compact and look like regular glasses, we need external computing power. If this processing power comes from the cloud, 6G is absolutely necessary. Transferring extremely large quantities of data to the glasses with video resolutions of at least 8K in stereo requires transport capacities of several hundred gigabits per second along with signal transit times of a tenth of a millisecond to enable natural reactions in real time. 5G does not have the capacity for this. Networks will also need to allocate computing power intelligently for the various 6G services, and this is where artificial intelligence comes in. In fact, AI will be ubiquitous in 6G networks.

The real internet of things

Although the internet of things is slowly taking shape and industrial and transportation applications have received a boost from 5G, universal

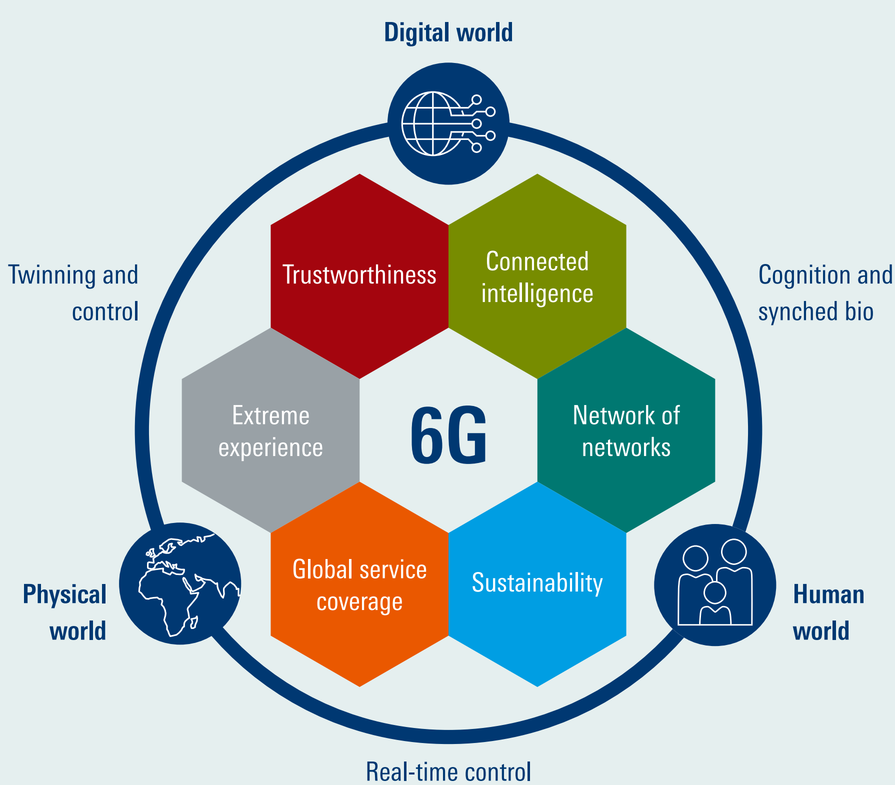


Fig. 3: 6G is set to meld the physical world (environment, machines), the digital world (data, virtual environments) and the human world in a symbiotic way, as shown here in the vision presented by the European Hexa-X initiative.

connectivity is only possible with 6G. Based on its technical configuration as well as its capacity, 6G should be capable of integrating any number of objects in homes, industries, road transport or infrastructure. This opens up networking opportunities that were never possible before. Embedded radio sensors can help monitor the condition of bridges and highways, making it easy to see when maintenance is needed. The RFID tags commonly used in retail sales and logistics can only be read from a short distance. Equipped with special sensors and a larger range, however, they could be used to monitor food quality.

The IoT boost will also change how connected radio sensors are powered, which presents a huge challenge for their large-scale deployment. The sheer quantity of these sensors as well as the degree of miniaturization makes it unfeasible to exchange the power cells. Since many applications are conceived for long-term deployment over many years, the sensors must be able to provide their own power. Zero energy devices and energy harvesting are two buzzwords here. Today's RFID sensors work with electromagnetic energy harvested directly from a nearby reader or scanner. But 6G sensors will have to make do without this convenience and obtain power from suitable local sources such as heat, light or motion. As with many other 6G topics, research in this area is still in its infancy.

A network of radio networks

6G will be not only an inexhaustible basis for the internet of things, but also a new kind of internet. The conventional internet is called a network of (computer) networks and 6G will be a network of radio networks. The monolithic structure of today's mobile networks will give way to a constantly changing heterogeneous network landscape (organic network). Commercial, private and public subnetworks of all sizes will be interconnected in this manner, ranging from the macrocells that exist today and provide coverage over an entire square kilometer – to attocells and zeptocells with coverage for a single room or vehicle. To automate the connection of a network to the overall network structure, as many network functions as possible need to be virtualized (described with pure logic). The network's function blocks must provide multivendor support for this abstract language and interpret it in compliance with the standard. Rohde&Schwarz is involved with the O-RAN initiative, which is already laying the foundations for this.

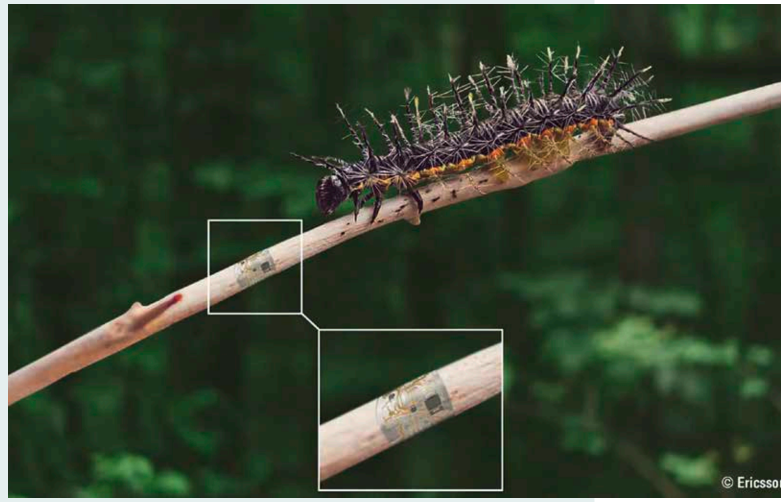


Fig. 4: Design study carried out by network equipment supplier Ericsson: zero energy devices can benefit more than just civilization. For example, a 6G IoT radio sensor could measure ecosystem data and transfer it to a processing center.

The race is underway

Initial discussions of 6G only began a few years ago, but since then a lot has happened in industry, research institutes and the political world.

Research initiatives have been set up around the world, financial support has been granted and alliances have been forged. Politicians understand that competitiveness – and the economic prosperity of their countries – may rest on equal participation in the 6G system while avoiding dependency. In the spring of 2021, Japan and the USA agreed to invest 4.5 billion dollars in 6G research. Europe has launched its flagship 6G project, Hexa-X, with organizations from nine different countries. Separately, the German Federal Ministry of Education and Research is providing 700 million euros in funding until 2025. In the short term, 250 million euros will go to four national research hubs. Rohde&Schwarz is also involved in these hubs as a partner. South Korea has an ambitious plan to invest some 195 million dollars over the next four years and will be ready for preliminary field tests by 2026.

6G RESEARCH AREAS

There is a need for further research and development in the following areas:

- **FREQUENCIES:** 5G is using the millimeter-wave range (> 20 GHz) for individual communications for the first time. But 6G will go much further and push into the still relatively unexplored terahertz range (300 GHz to 3 THz). It will also incorporate visible light and infrared as required. These high frequencies are the only way to achieve the extreme transmission rates targeted.

- **ANTENNAS**: at such high frequencies which correspond to short wavelengths, the antennas have dimensions in the millimeter range. Base stations will combine up to 60 000 of these antennas into arrays to supply simultaneous coverage for hundreds of mobile devices via individual directional beams. Smart reflecting surfaces are also under consideration as a way to pinpoint specific users. They could be deployed on building walls, for example, to transmit radio signals around corners.

- **ARTIFICIAL INTELLIGENCE (AI)**: AI will be a major hallmark of 6g. Insiders believe that without AI, 6G networks could not be affordable or even function in the first place. Their complexity is simply too extreme for conventional design and management methods. AI will be used in technical components as well as in network planning and monitoring. The ultimate goal is to achieve a zero-touch (self-optimizing) network in terms of cost, energy, spectral and operational efficiency.

- **VIRTUALIZATION**: all of the main network components should be defined and addressable via standardized abstract functions. This ensures that products from different manufacturers can be combined while leaving room for specific technical configurations.

- **SELF-POWERED SENSORS**: quantity-wise, myriads of miniature sensors will form the largest share of the internet of things. They will need to operate maintenance-free for prolonged periods of time while obtaining power through energy harvesting.

- **INTEGRATED RADIO, SENSOR AND COMPUTER NETWORK**: 6G will be much more than just a radio network. Integrated location functions will allow the position of network users to be pinpointed down to the centimeter. The network's processing power will also be massively distributed and harnessed either close to the network user or in remote data centers depending on requirements (edge, fog and cloud computing).

- **DATA INTEGRITY:** 6G networks will form the backbone of business and industry – even more than 5G. Countless business processes and services will be based on these networks. Data security is therefore critical. Users must be correctly authenticated with absolute reliability. Every connection will require encryption. Block chain technology is being considered as a way to avoid dependence on central instances in order to ensure data integrity.

- **ENERGY EFFICIENCY:** energy demands inevitably also rise when data communications grow exponentially. The energy consumed per bit transmitted needs to fall in order to keep energy efficiency in check.

And then there is China. Of course, China has no intention of giving up its strong 5G position simply because the next generation of technology has arrived. China's Ministry of Science and Technology is working with other ministries and government agencies to coordinate national resources and get 6G ready for deployment as quickly as possible.

Rohde & Schwarz has been a close partner to industry as well as a leading supplier of T&M equipment since the very beginning of the digital mobile communications era. The company's products and expertise are already in use today in various 6G research projects, and the company will provide the measuring equipment needed for 6G.

EDITORIAL TEAM

[1] David, K., Berndt, H.: 6G vision and requirements: Is there any need for beyond 5G? IEEE Vehicular Technology Magazine, Vol. 13, Issue 3, Sept. 2018.

CONNECTED CARS ARE COMING

Both established automotive manufacturers and industry upstarts are moving forward with autonomous vehicles. In addition to sophisticated sensors, fully connected vehicles are vital to autonomous driving. OEMs and suppliers around the world are relying on the C-V2X standard. Radio communication testers from Rohde & Schwarz have all the necessary functions for C-V2X testing – including 5G test case simulations.

Shanghai at rush hour. Want to merge? The name of the game here is honk and drive. If someone cuts you off, honk back. Want to reverse in the middle of an intersection to change direction? It happens. With any luck, you can avoid crashing into one of the countless e-scooters silently slithering through the gaps in traffic. Electric mopeds and small electric vans shamelessly drive on sidewalks. "The streets are just too dangerous," says Munich based consultant and Shanghai University of Finance and Economics (SUFE) graduate Julian Schneider. Especially tricky: trying to cross an intersection on foot while horns blare, fully aware that a green light does not mean it is safe to cross. Turning right on red is legal in China, just like

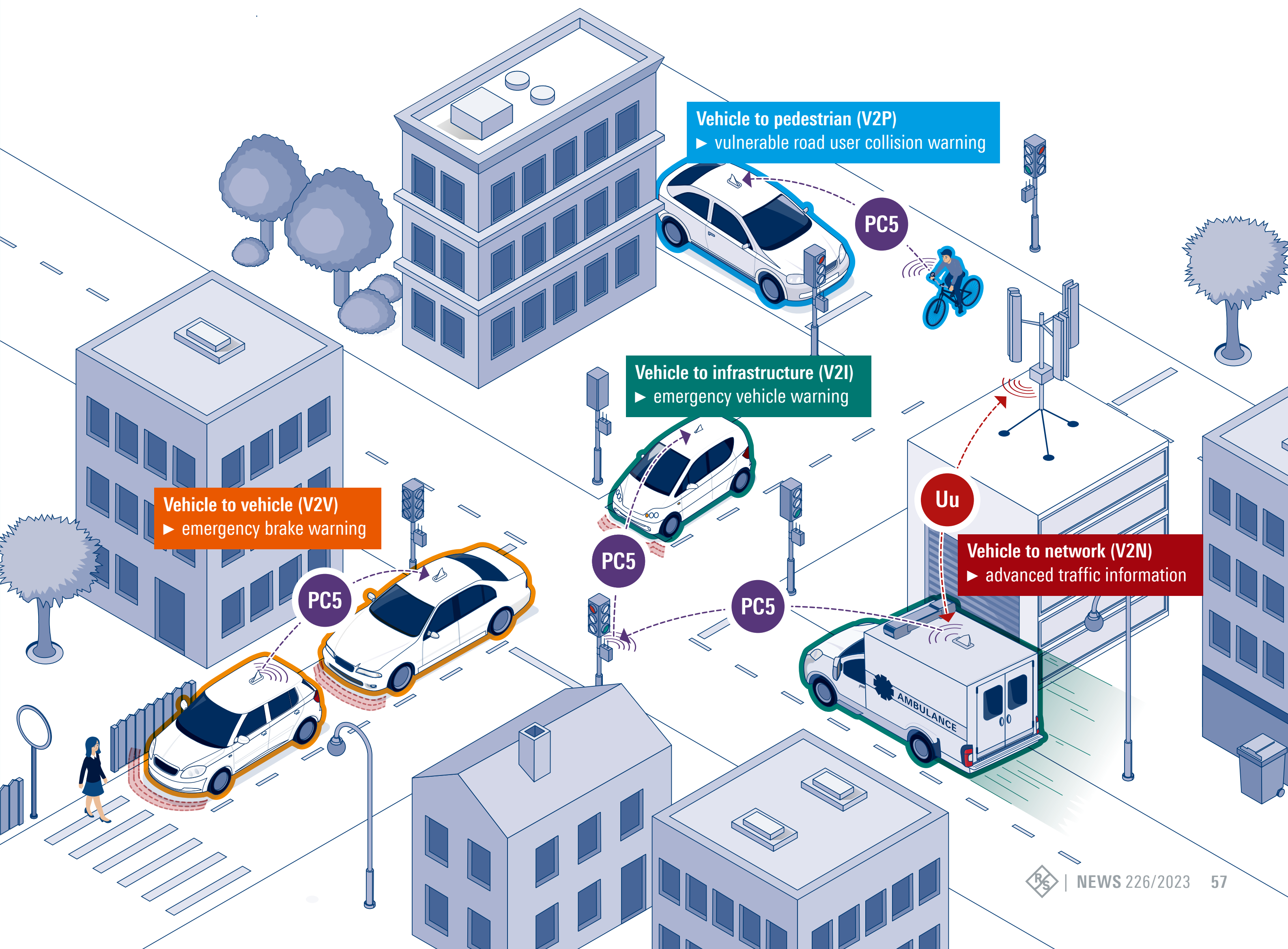


Fig. 1: A glimpse of the future – replacing steering wheels with displays requires reliable mobile communications in the vehicle.

in Canada and the USA. This all means more road fatalities than anywhere else in the world according to the latest World Health Organization (WHO) report from 2018. But the Chinese government wants to make things safer. Anything to bolster the country's technical expertise is more than welcome – such as connected autonomous transport.

Making a virtue of a traffic necessity

Chinese start-ups are pioneers in the future of automotive travel. The traffic chaos in Chinese megacities plays right into their hands. James Peng thinks these companies face especially tough challenges in China. He is CEO of Pony.ai, a robotaxi startup founded in 2016 and an industry giant with a market value of 8.5 billion dollars. He believes experience with unpredictable local Chinese roads is more valuable and the data will be more relevant than the results from the USA, for example. Pony.ai already has a fleet of 100 robotaxis in the southern Chinese city of Guangzhou covering an area of 800 square kilometers. This is another step in the commercialization of autonomous driving in China. Industry experts predict a global mass-market breakthrough by 2025. China is the biggest potential market. Millions of robotaxis are expected to be navigating Chinese roads by 2030. Pony.ai will have to share the market with strong, local competitors like Baidu, AutoX, and DiDi Xungking. These companies have also been running tests and working hard to refine their driver assistance systems.

US start-ups compete with the European automotive industry

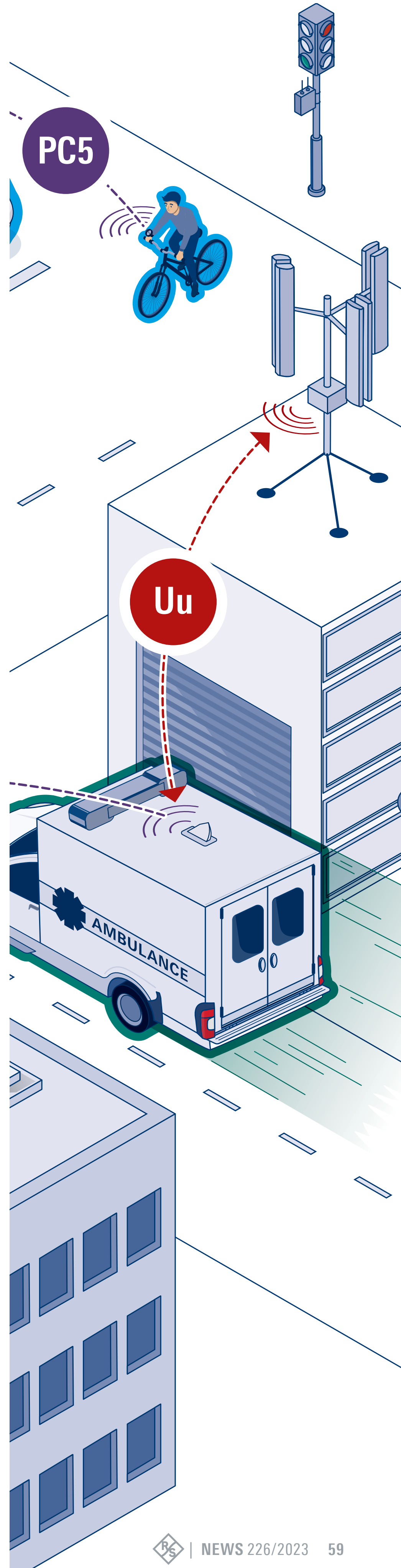
The USA is once again at the vanguard of connected autonomous vehicles (CAV). A favorable regulatory environment was created early on, particularly in California. Google's sister company Waymo racked up valuable test miles before the international competition and is still considered the benchmark for autonomous driving. Other companies have now also recognized the potential of California as a testing ground and are following suit.

The situation is very different in Europe. While the USA and China rely on the speed and agility of their start-ups, Europe is combining the efforts of their automotive industry and major IT firms. Some local projects provide automatic shuttles and people movers for the first and last mile of public transportation. Even though the pioneers come from different regions, Germany passed the first comprehensive law on autonomous driving up to level 4 in July 2021, allowing fleets of robotaxis to operate on German roads.

The role of C-ITS, V2X and 5G

Autonomy level 5 is often mentioned and designates driver assistance systems that are sophisticated enough to pilot a vehicle completely on their own (with full autonomy) and are safer than human drivers. However, level 5 is just a way station. Looking at the bigger picture, the ultimate goal are cooperative intelligent transport systems (C-ITS) that cover all forms of transportation and use technology to maximize road safety and efficiency. A wave of green lights would no longer be a rarity with connected traffic. C-ITS would also effectively prevent secondary accidents because a vehicle in front will tell other road users behind immediately when it starts emergency braking. Platooning is also a great opportunity for freight forwarders to save fuel. And once laws are amended to require only the lead vehicle in a platoon to have a safety driver, the technology would become even more attractive. But there is still a long way to go.

Connected transportation will only become a reality, once vehicles communicate with each other, surrounding infrastructure and traffic control centers. This principle is called



vehicle-to-everything (V2X) communications. It includes vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-pedestrian (V2P) communications.

5G provides an important technical foundation for V2X communications. This is no coincidence, since the automotive industry has been involved in the standardization process from the very start to make sure that 5G meets all its needs. It is the ideal standard for traffic connectivity. 5G has all the necessary features, including a high transmission rate, availability, reliability and short signal delays (latency). But cellular networks (C-V2X) – radiocommunications via intermediary base stations – can only cover a part of the communications demands. In dead spots or ad hoc situations, vehicles need to communicate directly. And that is where sidelink (PC5) interfaces come in. These have been around since LTE (4G). Independent of the situation at hand, V2X communications either flow over the cellular network or the PC5 sidelink.

New standards, new test cases

To make these visionary plans a reality, next generation vehicles must be 5G-ready. The automotive industry already has experience with cellular telematics in its mandatory emergency eCall system. However, compared to existing standards, 5G is much more demanding with a host of entirely new testing challenges for both car makers and suppliers.

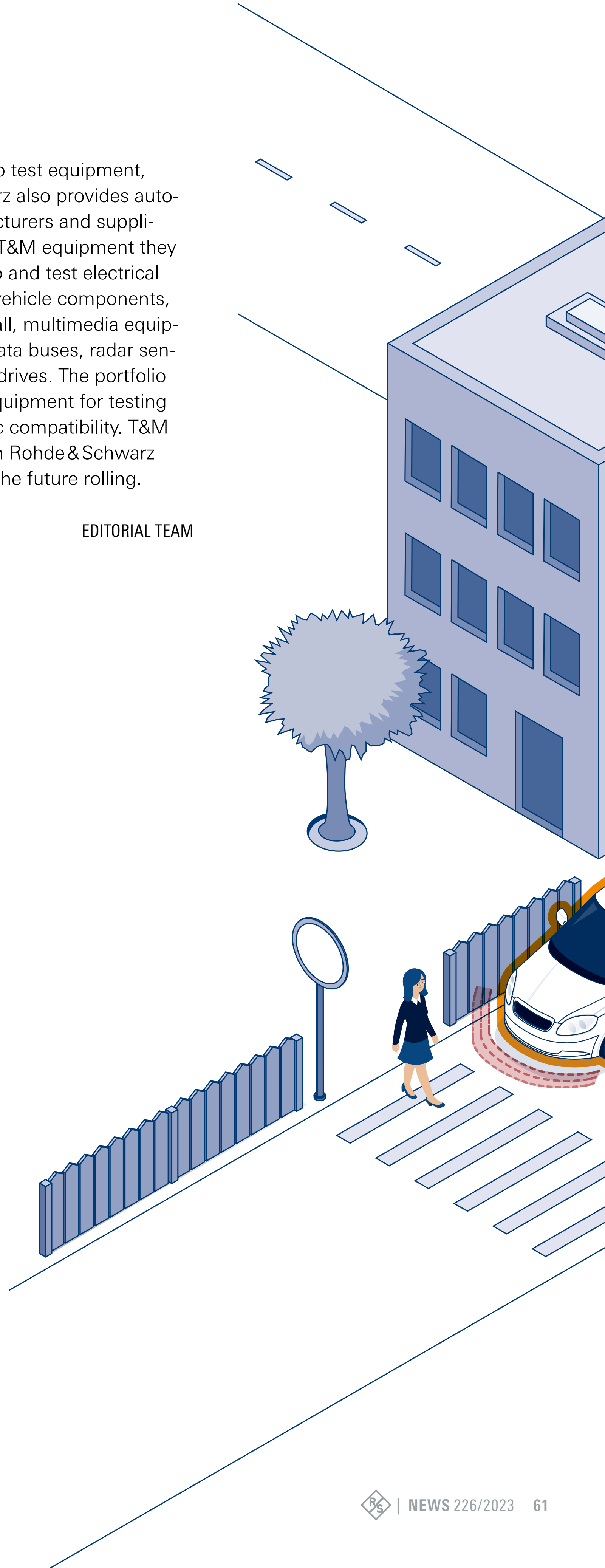
Rohde & Schwarz has a range of specialist measuring instruments for developers and system integrators, giving them everything they need to efficiently integrate a wide variety of wireless technologies, including mobile communications but also Bluetooth®, WLAN, and GNSS. Radio communication testers such as the R&S®CMX500 can simulate wireless networks with all their functions, measure and evaluate user equipment performance and allow customers to test any 5G application in the lab. Telematic units and entire vehicles

can face any kind of traffic situation, including those that do not yet exist. Being able to run such tests is hugely important for C-ITS development, because systems will need automatic processes that cover an enormous range of traffic situations. And if collecting real-world test data for a given scenario is not possible or feasible because of excessive costs, it can be simulated in a lab.

Vehicle air interfaces (antennas) are given special attention. Turnkey measuring systems automate the necessary tests and relieve manufacturers of time-consuming and error-prone full vehicle antenna testing (FVAT) procedures. In addition to (mobile) radio test equipment, Rohde & Schwarz also provides automotive manufacturers and suppliers with all the T&M equipment they need to develop and test electrical and electronic vehicle components, whether for eCall, multimedia equipment, vehicle data buses, radar sensors or electric drives. The portfolio also includes equipment for testing electromagnetic compatibility. T&M equipment from Rohde & Schwarz gets the car of the future rolling.

EDITORIAL TEAM

Fig. 2: The R&S®CMX500 radio communication tester can be used in C-V2X applications to test the vehicle-to-network (V2N) or Uu interface, the interface between the vehicle and the mobile network provider.



AERONAUTICAL RADIO DIGITALIZATION READY FOR TAKE OFF

Rohde & Schwarz has been working with research partners to develop the LDACS digital data transmission technology which will soon replace the common VDL Mode 2 in civil aviation and become the worldwide standard. This is opening up entirely new use cases for airlines and communications service providers.

In the spring of 2019, the German Aerospace Center's Falcon aircraft took off on six test flights with LDACS radio equipment on board.

Technical progress is not always about replacing analog technology with digital technology. Civil aviation provides an excellent example of how technology can advance. Voice communications between pilots and the tower still use double-sideband amplitude modulation (DSB-AM) that dates back to 1948. No one wants to replace this analog VHF technology (frequency range: 118 MHz to 137 MHz) with digital voice communications. Ultimately, analog radio has clear benefits that remain critical today, these include short delays, active monitoring by all participants and other features that digital radio still cannot replace.

Data transmission waveforms are a different story. Since the 1990s, aeronautical radio has involved more than just voice communications and has been expanded to include digital data transmission methods. VDL Mode 2 is the most common one.

Digitalization of aeronautical radio today means replacing older digital data transmission methods with new techniques offering better performance. Voice communications will continue to use analog technologies but digitalization will help to relieve some of its burden on the spectrum. This coexistence of analog voice communications and digital data technologies in air traffic control enables extremely high efficiency, reliability and operational safety that are both economical and future-proof.

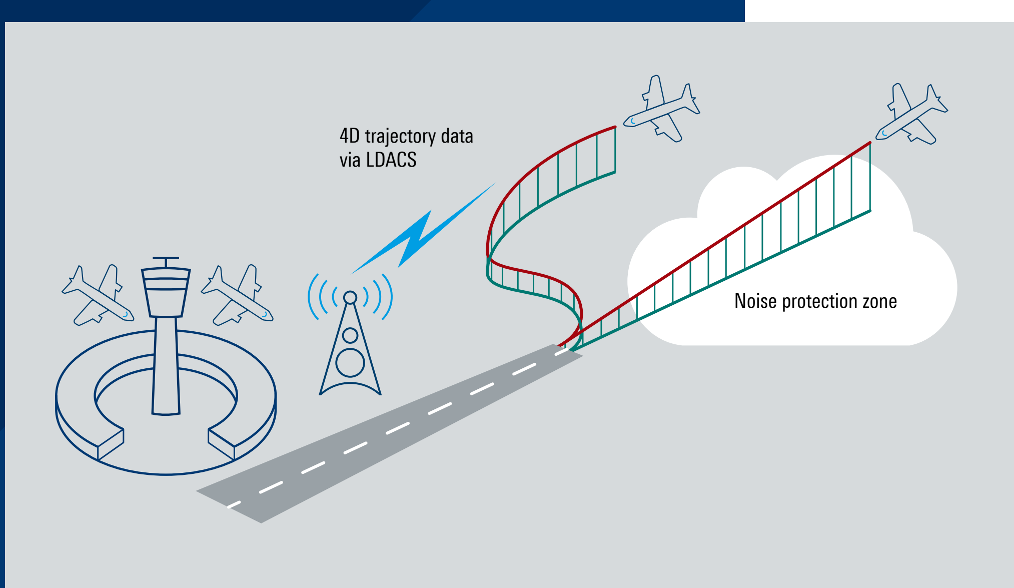
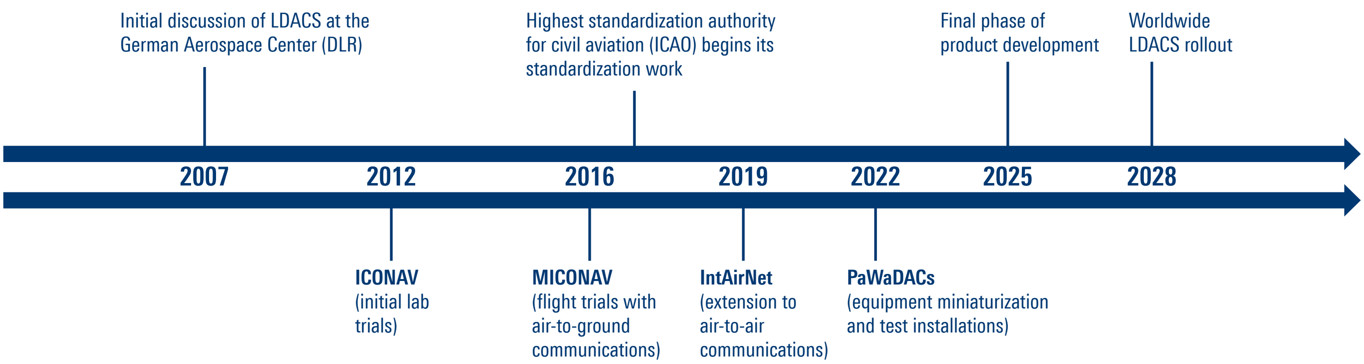


Fig. 1: Example of a 4D trajectory. When flying around noise protection zones in the future, more complicated maneuvers will be required instead of a straight approach. Pilots will obtain position data via the LDACS data link.

Fig. 2: From development all the way to a worldwide standard
In the development of LDACS, four major research projects have played a key role.
They are listed below the timeline and described in more detail in the info box at the end of the article.



Busy radiocommunications in a tight VHF spectrum

VDL Mode 2 is provided by air navigation service providers (ANSP). ANSPs are similar to mobile network providers in the private sector. Because VDL Mode 2 also operates in the VHF frequency band, the available spectrum must be shared between data transmission and voice communications. The usable bandwidths are relatively small, which means VDL Mode 2 can only transmit data at a few kilobits per second.

LDACS – moving to the L band

This is where the new L band digital aeronautical communications system (LDACS) comes into play. LDACS offers data throughput that is up to 200 times faster than VDL Mode 2. As the name implies, the key innovation here is data transmission in the L band. LDACS specifically uses portions of the frequency band reserved for aeronautical radio. LDACS uses interference suppression algorithms and is optimized for minimal out-of-band emissions and trouble-free operation alongside other aeronautical equipment operating in the L band.

New and appealing aviation services

Modern aviation demands the secure exchange of data. Otherwise, organizing air traffic would be impossible. LDACS reliably enables high data throughput that is secured with encryption. It supports a wide variety of new applications, such as the data links airlines need for flight crews to efficiently plan fleet operations. There are far more aircraft flying nowadays and air traffic controllers need to be able to distribute new navigation data more quickly to adjust flight paths in time when the situation changes in their airspace.

One of the first new LDACS applications uses its data link capabilities to extend or even replace slow VHF radio links in existing ATC systems with fast LDACS links. This will quickly and noticeably speed up data transmission without requiring the purchase of new systems. Another factor in favor of LDACS is its very simple path forward to a market launch.

Reliable and secure LDACS data transmission will also be used for new environmentally friendly navigation methods. The plan here is to select aircraft routes using precise coordinates in three-dimensional space that must be passed within rigidly defined time limits. The 4D trajectory concept can be applied when aircraft need to be dynamically routed in the vicinity of airports to avoid noise protection zones, as illustrated in Fig. 1.

The long-term goal is to manage the complete flight path from the departure airport to the destination exclusively with 4D trajectories, allowing for much more efficient and environmentally friendly use of airspace.

Aviation standards are crucial

Like all other systems on board aircraft, transceivers are also subject to international standards. Permits to fly are issued based on these standards to make sure that the technology on board is reliable and satisfies all air traffic safety criteria. The approval process is usually very onerous, taking anywhere from ten to twenty years. Since most companies cannot afford to wait this long, government research initiatives have been established to ensure industry involvement in the standardization process as early as possible. The German Federal Ministry for Economic Affairs and Climate Action has launched the aviation research program (LuFo) for LDACS. Rohde & Schwarz is part of the program and is joining forces together with project partners such as the German Aerospace Center (DLR) to cooperatively develop LDACS technology. Working groups are collaborating with the International Civil Aviation Organization (ICAO) to create and implement flight acceptance standards. Headquartered in Canada, ICAO is the highest standardization authority for civil aviation. It examines and integrates the most important documents in the standardization process.

Fig. 2 provides a concise overview of the history of standardization through to the product developments currently being planned.

As part of the recently launched LuFo project PaWaDACs (see information box), the technological cornerstone has been set, allowing product development of LDACS ground and onboard equipment starting in about 2025. The market launch is expected for 2028. Thanks to its early involvement in LuFo projects, Rohde & Schwarz has a competitive position in the race for market leadership among LDACS suppliers.

THOMAS BÖGL, ROHDE & SCHWARZ

FOUR MAJOR RESEARCH PROJECTS

Four successive research projects sponsored by the Federal Ministry for Economic Affairs and Climate Action (BMWK) have served to significantly advance the development of LDACS digital data transmission technology for civil aviation:

- **ICONAV (Integrated Communications and Navigation)**
  Along with the German Aerospace Center (DLR) and other project partners, Rohde & Schwarz worked within a consortium to develop a functional demonstrator for lab tests from 2012 to 2015.

- **MICONAV (Migration towards Integrated COM/NAV Avionics)**
  The ensuing MICONAV project delivered proof of operational reliability during flight operation. Between 2016 and 2019, an airworthy demonstrator was developed that also included highly accurate navigation functions. In subsequent lab and flight tests, it was possible to successfully test logging on and off four LDACS base stations that were specially built for the project as well as the handover from one ground station to another. Communications between the aircraft and the ground station functioned just as reliably in various situations such as flying overhead at a high altitude and during landing, takeoff and taxiing at the airport.

- **IntAirNet (Inter Air Network)**
  This project (2019 to 2022) extended the capabilities of the waveform to include direct connectivity between aircraft. This means that LDACS is no longer strictly bound to terrestrial infrastructure and can also be used for flight paths over oceans.

- **PaWaDACs (Pave the Way to Digital Aeronautical Communications)**
  The PaWaDACs project has been underway since 2022. It is focused on miniaturizing the equipment demonstrators and preparing a realistic test installation at two locations operated by the German air navigation service provider (DFS). Once this work is completed, the key technological steps needed for future LDACS systems will be securely in place. A solid basis will thus be available for developing new products for civil aviation. Rohde & Schwarz will not only be able to supply equipment for ground stations, but will also be well-positioned to offer solutions to its customers for use on board their aircraft.

Interview with Thomas Bögl, Director of Technology and Studies

"IT SOLVED THE CHICKEN-AND-EGG PROBLEM"

The L band digital aeronautical communications system (LDACS) officially kicked off in December 2016 when the International Civil Aviation Organization in Canada began drafting standards. Years of groundwork went into reaching this milestone.

Hardly anyone knows this better than Thomas Bögl. The Director of Technology and Studies at Rohde & Schwarz clearly saw the need for a long-term digital expansion of the analog aeronautical radio standard already in the late 2000s. Bögl worked with Thomas Richter, a senior engineer from predevelopment, and his department to launch R&D projects inside the company while making contacts at research institutions such as the German Aerospace Center (DLR). He was also prepared to fly 6000 kilometers from Munich to the International Civil Aviation Organization (ICAO) headquarters in Montreal, Canada at the drop of a hat.

NEWS: Mr. Bögl, when did you start working on LDACS?

Thomas Bögl: I first heard about LDACS in 2010 at a DLR meeting in Oberpfaffenhofen. DLR helped create the LDACS waveform. The DLR experts made a very convincing case that new digital waveforms were needed to ease pressure on analog voice communications. New products were clearly needed. Since the DLR does not develop products itself, a collaboration between research and industrial partners made a lot of sense. The meeting was also the beginning of a highly productive aeronautical research (LuFo) project partnership with the DLR.

Analog voice communications have long proven their worth in ATC communications. Where did you see signs that it had reached its limits?

Today, air traffic controllers handle almost as many aircraft as they did before COVID-19. And the numbers are growing rapidly. We could see this trend 15 years ago. Another factor is that hiring more employees to shoulder the workload is not possible – there are simply not enough parallel voice channels. The only way to relieve pressure on the system is to create a parallel data link for instructions that do not require direct voice communications between pilots and air traffic controllers, such as non-safety instructions when the aircraft is still on the ground. Of course, VHF data link technology has been around for years but it has limited data throughput and cannot effectively relieve voice communications over the medium or long term. It soon became clear that aviation would need a more powerful digital data link technology.

LDACS also opens new use cases. Which are the most important ones and why?

The first and most important use case is providing sufficient data rates and encryption in existing systems. LDACS in the L band will be a powerful sibling to the

Test flights 2019: waveform development and T&M equipment from Rohde & Schwarz provided the radio links and stored all the collected data totaling over 12 terabytes.

> "Of course, field trials in April 2019 were an absolute LDACS highlight when we installed an LDACS demonstrator in the DLR research aircraft."

existing VHF data link. An LDACS data link is like a quasi broadband VHF data link, making it relatively easy to expand existing systems.

LDACS also has its own navigation function. If GPS or other navigation systems are unavailable to an aircraft, LDACS can act as a backup system and provide positioning information. LDACS boosts efficiency in aeronautical radiocommunications, while also helping to improve aviation safety.

Your work required you and your team to travel to Montreal to the ICAO headquarters very early on. Why not go to the European regional office in Paris or to the German air navigation service provider (DFS)?

The members of the ICAO communications panel meet solely at the headquarters. Only they have the power to create new working groups with a mandate to standardize new aviation technologies. DFS uses technologies that are approved for air traffic control, but it is not authorized to carry out standardization work on its own.

Generally, airlines and airport operators do not invest in new technology until new equipment is nearly ready for the market. And component and equipment manufacturers want to see that a market exists before investing in development. Was your visit to the ICAO also vital to solving this traditional chicken-and-egg problem? Once a decision is made at the highest level, everyone has planning certainty.

Yes, our visit to the ICAO solved the chicken-and-egg problem and marked the start of international targeted LDACS activities. A forum was quickly created with the establishment of a new technology working group, where anyone interested and affected by LDACS could officially meet and share ideas. It also served as a base for activities that looked beyond standardization work. The Avionic Task Force was founded and, working under the ICAO mandate, it brought together all of the companies involved in aviation systems to identify and overcome any remaining hurdles. Thomas Richter is in charge of this working group. As the project leader for LuFo projects at Rohde & Schwarz, he planned and organized the flight trials. He played an important role in LDACS happenings. Without his tireless commitment, the many LDACS activities at Rohde & Schwarz would not have been possible.

Which organizations and agencies need to cooperate to successfully introduce global standards such as LDACS?

The ICAO and EUROCAE are the most important. However, major air navigation service providers such as EUROCONTROL also play a role since they provide the formal basis for rolling out and operating a new system. Future operators and LDACS users are also very important. Airlines and aircraft manufacturers need to signal their interest in a system and convince companies to invest a share of their R&D budget and reach the point where products can actually be marketed.

A five-member team headed off to Montreal back then. How has interest in LDACS evolved since?

Some 200 companies and organizations attended one of the latest LDACS webinars organized by the DFS. They are learning about LDACS while pursuing their own activities here. Despite the growing competition, Rohde & Schwarz is the only company said to be interested in supplying LDACS products for aircraft and ground infrastructure.

What has been your biggest motivation over the past 15 years?

Several things. One is that the international aviation community has taken up many of our LDACS proposals. For example, we have shown how to cost-effectively expand aircraft and ground installation infrastructure with LDACS. I am also pleased to see many companies and organizations talk to us about the technology. We are considered a top authority here.

Of course, field trials in April 2019 were an absolute LDACS highlight when we installed an LDACS demonstrator in the DLR research aircraft to show what the new waveform could do live and in flight. We set up four LDACS ground stations in southern Germany and the aircraft onboard system successfully communicated with the stations during the flight. The DFS granted all necessary approvals for realistic test flights. We could then fly through airspace along with normal air traffic. These were first flights to demonstrate LDACS live, generating a huge media response. That day the DLR website did not have any reports about Mars missions or the ISS but focused entirely on the LDACS test flights for our project.

As an engineer, how do you cope with the bureaucracy of standardization?

I am in fact involved with the technology, but with a special focus on the usability and economic efficiency of future solutions. These two aspects are very important. If a new technology has little customer value, no one will buy it. And if the technology does not work and is financially unappealing, it will never be introduced in the first place. Even exceptional customer value can't help in such a case.

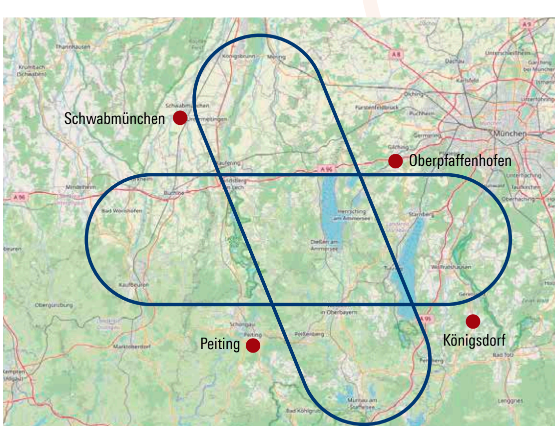
Yes, standardization work can be very bureaucratic. We basically share this work with the DLR and the DFS. Both are partners in the current LuFo project PaWaDACs. They also both play a key role in the standard committees at the ICAO and EUROCAE. The division of labor lets us focus on the technology and customer benefits, while the DLR and the DFS include our results in the standards.

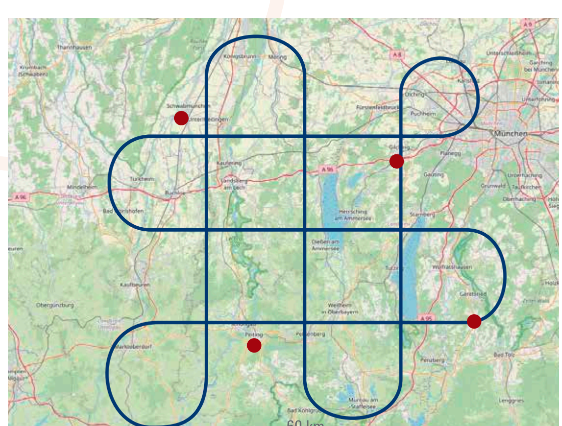
How would you sum up what you have achieved so far? And what do you see as the next major milestone for LDACS?

I am very positive about our achievements. Right now, many different parties are interested in LDACS. Standardization should be completed in the next calendar year. The main requirements for us as a company are fulfilled. This means we can have the right products available for the projected market launch in 2028 and tap even further into the civil avionics market.

EDITORIAL TEAM

The first MICONAV test flight was routed over four LDACS ground stations that were specially set up for this project in southern Bavaria. Two of the stations had transmitters for collecting navigation data. The other two had transceivers for digital aeronautical radio data. The flight paths were planned to allow testing of the handover process (top left) as well as various triangulation scenarios using two to four ground stations (bottom left).





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5 kW HF HIGH-POWER TRANSMITTERS FOR AIR TRAFFIC SERVICE

The R&S®SK4105 HF high-power transmitters combine high transmission power and reliability with a small footprint, making them ideal for air traffic service over large areas under harsh conditions such as those in Greenland.

Fig. 1 (right): Selected aircraft radio stations along the Greenland coast.

Greenland covers over two million square kilometers and is the largest island in the world with a mere 57 000 inhabitants. The airspace is extensive and the transmitter stations remote. Danish air navigation service provider Naviair handles air traffic in the lower airspace via the Flight Information Centre (FIC) in Greenland. In addition, Naviair operates several HF and VHF radio systems at strategic points along the Greenland coast. Communications run mainly through the FIC in the southwestern capital Nuuk. The HF transmitters there are soon to be replaced. In summer 2023, Rohde & Schwarz will supply the low-maintenance and compact R&S®SK4105 shortwave transmitters, which are ideal for such a demanding environment. The R&S®SK4105 transmits in the frequency range from 1.5 MHz to 30 MHz with up to 5 kW transmission power. This high transmission power, enabling long-range radio links from the ground station to the aircraft.

Liquid cooling for a compact and low-maintenance design

Liquid-cooled high-power amplifiers are connected downstream from the signal source. Liquid cooling systems have been widely used in TV and radio station transmitters for years. They are a unique selling point for air traffic control (ATC) transmitters with their compact footprint, reduced maintenance requirements and high reliability. The R&S®SK4105 and pump unit fit into a 19" rack. Air-cooled transmitters from other companies require up to four times as much space and need more maintenance due to mechanical wear and tear.

The coolant flows through an aluminum block, maintaining an optimum operating temperature for the transmitter module mounted on top. This also relieves thermal stress on any other components in the housing and increases the reliability of the overall system. This is very important for transmitters that perform safety-critical tasks and even more for those in remote, snow-bound locations that are very difficult to access. Under such operating conditions, waste heat from the transmitter housing can be used to heat the transmitter shelter.

Overall power requirements and operating costs are lower compared to air-cooled HF transmitters. In regions without Greenland's permafrost, liquid cooling has another advantage. Since the cooling is independent of the outside air, the transmitter requires far less air conditioning.

Future-proof HF transmitter for ATC tasks

The R&S®GX4100 exciter is a key component of the R&S®SK4105 HF high-power transmitter and is already used in several 1 kW HF coastal radio stations for ship traffic in Greenland. The software defined exciter meets EUROCAE ED-137C criteria, meaning new transmitter functions can be integrated and adjustments made to future radio standards with little effort. As part of the CERTIUM® portfolio from Rohde & Schwarz, the HF high-power transmitter is compatible with other hardware and software in the CERTIUM® series and can be expanded to fit any application.

EDITORIAL TEAM

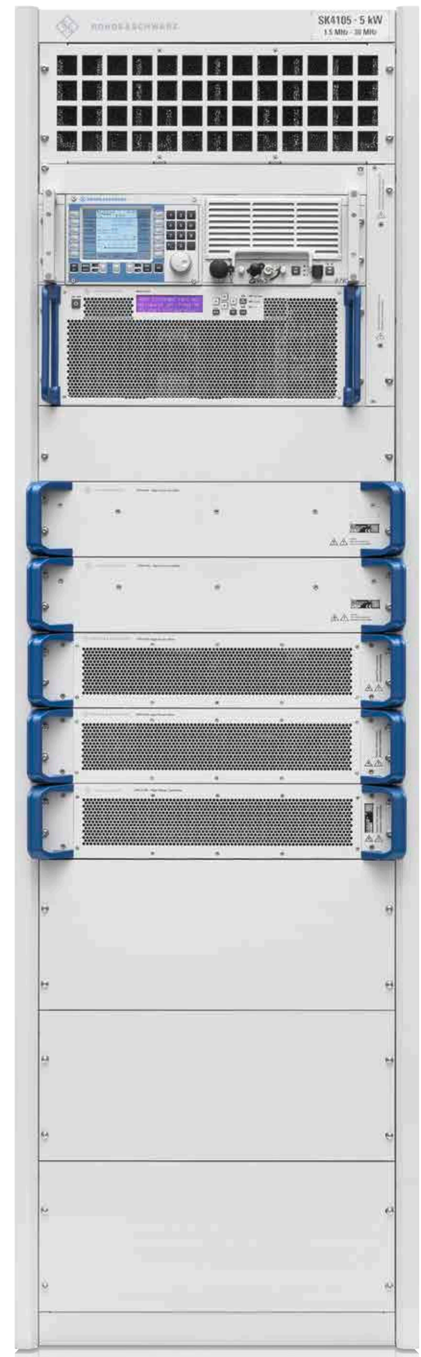

Fig. 2: The R&S®SK4105 HF high-power transmitter can be configured in variants with transmission power from 150 W to 5 kW.