Educational Note

ACCELERATING RESEARCH INTO QUANTUM COMPUTING

► Using serious test and measurement tools to enable serious research

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Contents

1 Overview

Quantum computing has the potential to conquer problems that are far too complex for classical computing. Examples include the simulation of chemical substances for drug design and the modeling of systems such as the global climate. For decades, the reality of quantum computing lagged far behind the theory. In the last several years, serious research has been ramping up all across the world, and the imagined applications are at once fascinating and potentially significant. Serious research benefits from serious tools, and this includes test and measurement equipment: vector signal generators, vector network analyzers, signal analyzers, high-speed oscilloscopes, and more. This white paper provides a brief overview of quantum computing, sketches the current state of research, and outlines test and measurement tools from Rohde & Schwarz that offer meaningful advantages to those performing research in the field of quantum computing.

2 Accelerating Research into Quantum Computing

As with any potentially revolutionary technology, there is a lot of hype and speculation surrounding quantum computing: it will render traditional cryptography obsolete; it will radically change blockchain and digital currencies; it will produce miracle drugs in minutes instead of months.

While the reality will likely be somewhat less dramatic, quantum computing is well-suited to the inherent complexity of natural systems. Examples include the simulation of chemical substances for drug design or solid-state batteries, and the modeling of complex systems such as the global climate or global pandemics. These are profoundly difficult problems due to the complex interactions of myriad variables, many of which have multiple degrees of freedom.

2.1 Catching up with theory

Because classical computers are linear and deterministic, it can take a long time to work through the permutations of complex scenarios before eventually reaching an answer. In contrast, a carefully crafted quantum algorithm harnesses the power of "quantum bits" or qubits, using parallelism and probability to explore possible scenarios and solutions. This is how quantum computing can solve certain categories of highly complex problems in minutes rather than the months or years needed by a classical computer.

The first serious proposals emerged more than 40 years ago (c.1980), but for several decades the reality of quantum computing lagged far behind the theory. Today, serious research is underway all across the planet, and the imagined applications are at once fascinating and potentially significant.

2.2 Building on the foundation

All of the foregoing is the foundation of this white paper. The narrative starts with a brief comparison to establish a baseline for those who are new to quantum computing. From there, it sketches the current state of industrial and academic research (as reported in public sources). The concluding section outlines test and measurement tools from Rohde & Schwarz (R&S), highlighting the potential contribution to those who are researching quantum computing. In our view, serious research benefits from serious tools, and this includes several types of test and measurement equipment: arbitrary waveform generators (AWGs), vector signal generators, vector network analyzers (VNAs), signal analyzers, high-speed digitizers, and mixed-signal oscilloscopes.

3 Comparing Quantum and Classical

In the early 1980s, Paul Benioff and Richard Feynman each described the possibility of quantum computing. During this period, the ever-quotable Feynman delivered one of his most memorable comments: "Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look easy."

Thus, research began in earnest roughly 40 years ago; however, simple quantum computers were not demonstrated publicly until the late 1990s. More recently, 30 years down the road, the pace and intensity began to increase. Even so, all agree that there is still far to go until the technology becomes affordable, convenient and accessible.

3.1 Applying potential lessons

As quantum computing continues to take shape, researchers may be able to apply some of the lessons learned in semiconductors, classical computers, and software over the last 80 years. For example, classical computing has undergone tremendous evolution, gradually morphing from room-sized machines built with vacuum-tube transistors and limited memory, to desktop workstations with cathode ray tube (CRT) displays, to the powerful multifunction smartphones that we can hold in one hand.

For decades, the growth in computing power kept expanding according to Moore's Law. That is, the number of transistors in a densely packed integrated circuit (IC) doubles roughly every two years. However, and somewhat ironically, with continued miniaturization, quantum effects are emerging as one of the key obstacles causing the deceleration of Moore's Law.

The reason: at transistor sizes of less than 5 nm, effects such as quantum tunneling become problematic (e.g., signals may disappear on one side of a barrier and reappear on the other). In addition, heat dissipation due to leakage current becomes a significant issue. This is one of the reasons why cooling systems for supercomputers continue grow larger and more expensive.

3.2 Summarizing the differences

Thus, as the potential power of classical computing begins to plateau, interest in quantum computing will continue to rise. For that reason and more, it is important to consider the radical differences between classical and quantum computing.

For starters, quantum has its own language: qubit, superposition, entanglement, annealing, and more. Table 1 provides some essential context, offering a snapshot of the differences between classical and quantum computing.

Classical computing	Quantum computing
Binary; one OR zero	Quantum bits (qubits); zero OR one, zero AND one
Linear & deterministic (e.g., on or off, one or zero)	Parallel & probabilistic (e.g., vectors)
Scalability: finite powers of 2	Scalability: exponential
Boolean logic; uses logic gates	Superposition, entanglement, measurement; uses quantum gates
Applications: universal	Applications: expected speedup for specific uses such as simulation of complex natural systems; cryptography; machine learning; system optimization; advanced search algorithms

Table 1. This side-by-side comparison highlights the new thinking needed to grasp, create and apply quantum computing.

Today, a quantum computing system is radically more difficult to implement and operate than a classical-based system. Those challenges intensify when trying to increase the number of qubits in a system. As with any computer, more parallel data values correspond to more computing power. Thus, increasing the number of qubits in a system is a key objective for all who are architecting quantum computers.

Research is also focusing on the ability to control quantum computers with high precision while maintaining coherence and scalability. This requires very careful design of two elements: the interface with the control environment; and an exceptionally quiet operating environment (e.g., extremely cold temperature and ultra-high vacuum).

3.3 Acknowledging a key similarity

At a fundamental level, one crucial concept remains the same: the importance of algorithms. With either type of computer, an algorithm is a sequence of instructions that will, for example, perform some type of computation or solve a particular class of problem.

Running an algorithm consumes resources, most commonly measured in terms of time (e.g., number of steps) and storage (i.e., memory). Different implementations of the same algorithm may differ in efficiency and the use of resources. The depth and breadth of the available resources has implications for the amount of time it takes for the algorithm to reach a solution.

Quoting computing pioneer Ada Lovelace: "In almost every computation a great variety of arrangements for the succession of the processes is possible, and various considerations must influence the selections amongst them for the purposes of a calculating engine. One essential object is to choose that arrangement which shall tend to reduce to a minimum the time necessary for completing the calculation."

As suggested in Table 1, the potential advantages of quantum computing are exponential in terms of processing and storing information and in terms of speedup versus classical computing. Even so, there are drawbacks. For example, when a result is measured, the state of each qubit collapses probabilistically to either zero or one, yielding just one bit of information per qubit.

Given this probabilistic collapse, quantum algorithms must be repeated many times to build statistical outcomes and finally concentrate a large probability on the correct result. This fundamental characteristic of the architecture restricts the speedup advantages of quantum algorithms to only certain types of problems.

As a result, this fact has been a guiding light for researchers who have examined a variety of common problems, seeking quantum algorithms that provide exponential speedup versus the performance of binary machines. Two of the best-known examples are Shor's algorithm for factoring and the Harrow, Hassidim and Lloyd approach to solving a linear system of equations. In both cases, the combination of quantum circuits, qubits, and the quantum algorithm, produces much faster convergence on a result (i.e., "measurement") than with classical computing.

Bringing Lovelace's wisdom to the present, the algorithm is the thing, whether it runs on a classical or quantum "calculating engine." In all cases, it is essential to optimize the combination of problem, algorithm, and computing engine.

4 Expanding the Potential

One of the most accessible introductions to quantum computing is a YouTube video produced by *WIRED* magazine.[1] A leading researcher from IBM explains quantum in five levels of difficulty to five different people: a child, a teen, an undergraduate student, a graduate student, and a professional. The gradual progression through different levels of complexity and abstraction is engaging and informative.

One of the key takeaways is especially interesting: the world won't really know what quantum computing can do until many people spanning disparate disciplines try it and perform new experiments.

To enable this type of engagement, many companies are providing access to quantum computing through the cloud. One hope is to drive further advancement (and interest) as users come up with quantum-based solutions to increasingly diverse and demanding problems. Another is the anticipated (and hoped for) democratizing effect of widespread access: attracting more people from a wider variety of backgrounds will enable greater understanding, use, and influence.

4.1 Pursuing serious research

Although quantum computing is becoming increasingly present and accessible, the underlying technologies remain at an experimental stage. Many organizations are actively investing in quantum computing, and the roster of known participants includes a veritable "who's who" from industry and academia around the world. Tables 2 and 3 offer a variety of representative examples.

Examples: Industry	
Established players	**Startups**
Alibaba (Aliyun) Amazon (Amazon Braket) Google Quantum AI Lab Honeywell IBM Quantum Intel Microsoft Toshiba	Atom Computing D-Wave IonQ IQM Rigetti Silicon Quantum Computing Xanadu

Table 2. This is a representative list of companies, new or established, known to be active in the development of quantum computing.

Examples: Academia		
Asia	**Europe**	**North America**
Fujitsu RIKEN, the Institute of Physical and Chemical Research Tata Institute of Fundamental Research (Mumbai) University of New South Wales University of Science and Technology China University of Sydney	Chalmers University of Technology Delft University of Technology ETH Zurich FZ Jülich Max Planck Institute Paris-Saclay University University of Cambridge University of Innsbruck University of Oxford Walther Meissner Institute	California Institute of Technology Harvard University Massachusetts Institute of Technology National Institute of Science and Technology (NIST) Princeton University University of California, Berkeley University of Chicago University of Maryland, College Park University of Waterloo Yale University

Table 3. Around the world, numerous universities and research institutes are striving for new advancements in quantum computing.

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[1] View the video at https://www.youtube.com/watch?v=OWJCfOvochA

As noted earlier, building and running a quantum computer is difficult and complex. The challenges intensify as researchers attempt to add computing power by increasing the number of qubits in a system. Qubits have proven to be highly susceptible to noise, internal or external to the computer. Keeping a system stable, with a low error rate, for an extended period of time, is essential to reliable operation. The quest for stability has implications that extend to a variety of areas: cryogenic cooling or ultra-high vacuum conditions; the purity of the laser and radio frequency (RF) signals used to manipulate qubits; and more.

To reach these goals, university and industrial research teams are investigating various hardware platforms. The development of quantum platforms is supported in many ways by modern microwave technologies. For example, laser-based optical systems for quantum computing (e.g., trapped-ion and cold-atom qubits) require microwave devices to operate acousto- and electro-optic modulators, or to directly drive atomic-hyperfine and Zeeman transitions in the microwave domain. Because these transitions form qubits with long coherence times (e.g., the period for which a value is reliably stored) of up to tens of seconds, operation without large errors requires extremely stable microwave equipment.

For quantum systems with all transition frequencies in the microwave domain, quantum processors based on superconducting circuits and spin qubits in semiconductors have shown high potential to be scalable at low-error rates. To eliminate thermal noise, these microwave systems need to be cooled to cryogenic temperatures near absolute zero.

External control of quantum systems typically occurs at room temperature, and this is performed using high-performance microwave equipment. A pure and low-noise microwave signal helps to reduce the loss of quantum information potentially introduced by the qubit control tone.

5 Applying Serious Tools

In the realm of quantum computing, six types of test and measurement tools are especially relevant: arbitrary waveform generators (AWGs), vector signal generators, vector network analyzers (VNAs), spectrum analyzers, high-speed oscilloscopes, and high-speed digitizers.

5.1 Mapping onto a quantum architecture

Figure 1 illustrates a variety of typical connections and roles relative to an example quantum architecture. The quantum processor is housed inside a cryostat (lower middle) that maintains millikelvin temperatures. In this configuration, microwave signals (upper right) control the processor. During installation and set-up, calibration processes (upper left) are performed using test equipment: system characterization is performed using VNAs and spectrum analyzers; and level and timing alignment is done using oscilloscopes.

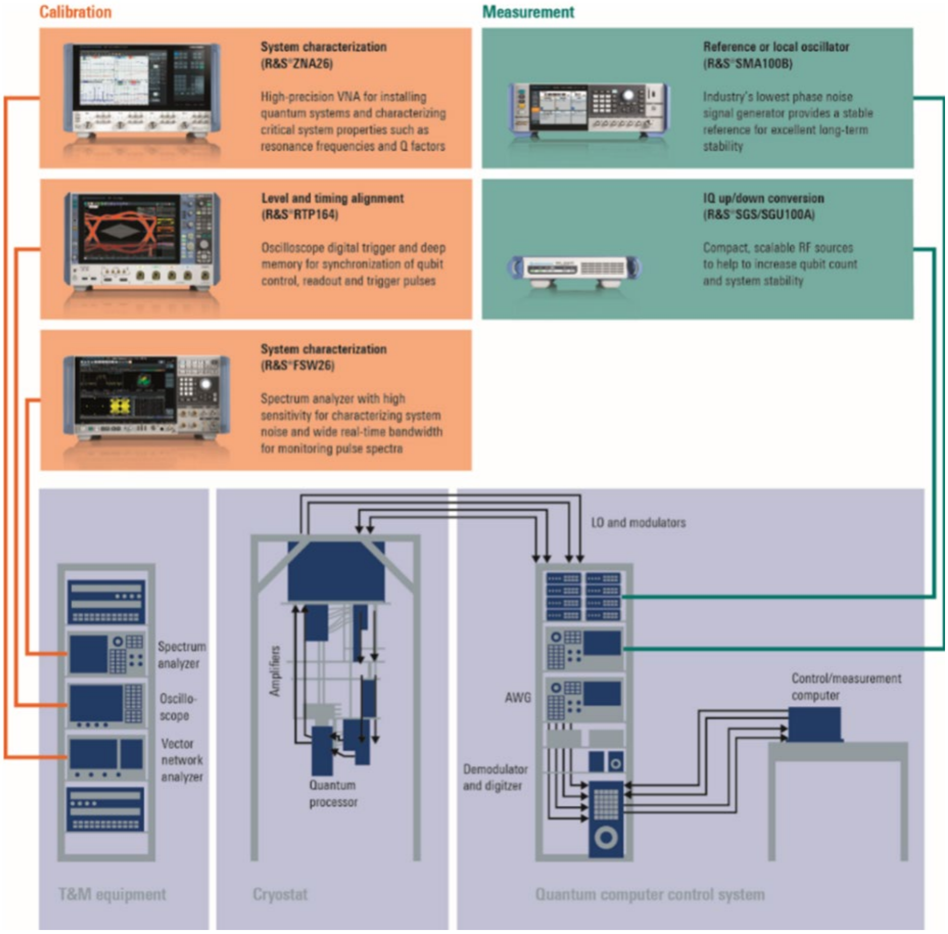

Figure 1. In this example architecture, test and measurement equipment enables better results in a variety of essential processes.

Within the control system (lower right), multi-channel AWGs are essential to obtaining high quality, multi-qubit control by generating both RF and microwave pulses with optimized shapes, as required. The output of high-resolution AWGs can be applied in one of two ways: directly at frequencies of less than a gigahertz, for example, to activate interactions between qubits; or up-converted to higher frequencies using external I/Q modulators or inputting them to a vector signal generator.

In the process of reading out the results of a quantum computation ("Measurement," upper right), high-performance microwave signal generators are essential because they significantly mitigate errors due to phase drifts. During the readout, the quantum system interacts with a pulse in the readout circuit, encoding information about the qubit state in the amplitude and phase of the readout signal. This information needs to be extracted during a time interval much shorter than the coherence time of the qubit. This has major implications for the performance of the cryogenic detection equipment that follows the quantum system, the room-temperature digitizers, and the digital-signal-processing function.

5.2 Highlighting R&S offerings

At Rohde & Schwarz, we believe exceptional tools help accelerate progress by enabling researchers to spend more time focusing on their work. For those pursuing development of quantum computers, we offer exceptional instruments in four major categories: vector signal generators; vector network analyzers; spectrum and signal analyzers; and high-speed oscilloscopes.

5.2.1 Vector signal generators

Vector signal generators are used in the control of qubits and the readout of results. On the control side, an exceptionally clean and stable RF signal contributes to greater system stability, thereby reducing the effects of quantum decoherence that cause errors and therefore loss of information. On the readout side, an RF source is an important building block because it helps reduce the number of errors that must be corrected when reading out computational results.

Here, our exemplar is the compact R&S®SGS100A SGMA RF source (Figure 1). This low-noise performance device helps increase qubit count and stability. It also lends itself to multi-channel operation, which is necessary when scaling up a quantum-computing system.

Figure 2. The R&S®SGS100A is the industry's smallest fully integrated vector signal generator, and its space-saving design simplifies system integration.

Another example is the R&S®SMA100B RF and microwave signal generator. Providing the purest output signals while maintaining the highest output power level, it delivers maximum performance without compromise.

With these sources and more, R&S is combining its RF expertise with the software and system know-how of our solution partners in the pursuit of a complete solution for these applications.

5.2.2 Vector network analyzers

Another key area of research is the quest for new materials and cleaner fabrication processes that can be applied to quantum-computing chips. Using spin qubits as an example, desirable materials include those that can enable quantum computing at higher temperatures, thereby reducing the size and cost of the associated cooling systems.

As developers create new quantum-computing chips, they need test equipment that can accurately determine specific properties relevant to quantum computing. Full characterization of the new materials and devices must cover several key aspects: measure and understand electrical properties in detail; perform full characterization across a wide frequency span (e.g., 10 MHz to 40 GHz); and provide better understanding of the processor as whole by identifying undesired resonant frequencies.

To obtain detailed feedback from new fabrication runs, developers can also use a high-performance VNA and a two-tone measurement technique to quickly determine resonant frequencies and key quality factors of the test chips. These results can be directly mapped to the coherence times of the resulting quantum system.

A VNA can also be used during the installation of the room-temperature and cryogenic microwave setups (please refer back to Figure 1). A DUT-centric operating concept enables efficient characterization of all RF components, active or passive, in the microwave system, thereby ensuring optimal performance of the whole setup. In addition, the VNA can assist in the debugging of individual quantum computing chips.

R&S offers a range of high-performance network analyzers that can address these needs. In particular, the R&S®ZNA vector network analyzers can help determine the properties of materials used in new quantum-computing devices (Figure 3). Key measurement capabilities include multi-tone capabilities that accelerate measurement times and multi-port measurements that enable measurements of multiple chips simultaneously.

Figure 3. The R&S®ZNA high-end VNAs combine touch-only operation with a DUT-centric approach to create a powerful, universal and compact measurement system for characterizing passive and active devices.

5.2.3 Spectrum and signal analyzers

To read out quantum information with high precision, one key success factor is careful design and verification of the detection equipment between the quantum chip and the room-temperature digitizer. The detection equipment includes superconducting parametric amplifiers, which operate close to the quantum limit of amplification, and ultra-low noise semiconductor amplifiers. To help verify the performance of these amplifiers -- and the complete detection setup -- high-sensitivity R&S spectrum analyzers are ideally suited to the measurement of noise performance and compression characteristics (e.g., nonlinear behavior).

Figure 4. With 1 GHz of analysis bandwidth, outstanding phase noise of < –127 dBc/Hz at 10 kHz offset, and high dynamic range, the R&S®FSVA3000 is a great choice for measuring wideband signals, analyzing frequency-agile signals, linearizing power amplifiers, and more.

In addition, R&S spectrum analyzers are useful for the measurement and calibration of I/Q mixers, especially the detection of undesired sidebands. A third relevant application of a spectrum analyzer with real-time capabilities is the reliable detection of short, sporadic interference signals.

Example models include the R&S®FSVA3000 and R&S®FSW signal and spectrum analyzers. The R&S®FSVA3000 is the right instrument for demanding signal analysis applications, offering outstanding phase noise and high dynamic range (Figure 4).

5.2.4 High-speed oscilloscopes

Another key measurement task is the precise temporal synchronization and alignment of the microwave pulses and triggers that are the basis of all quantum algorithms. In this application, high-speed oscilloscopes enable verification of the synchronization of readout and control pulses across multiple qubits. Key capabilities include real-time measurements of signal integrity and time-correlated analysis of multiple signals. Advanced oscilloscopes also support detection of undesired jitter events, thereby making an essential contribution to the stability of the whole quantum setup.

Figure 5. R&S®RTP oscilloscopes are ideal for precise measurements of high-speed signals due to their flat frequency response, high effective number of bits, and large spurious-free dynamic range (>60 dBc, excluding harmonics).

Here, R&S®RTP high-performance oscilloscopes combine exceptional signal integrity with fast acquisition rates (Figure 5). Dedicated ASICs for acquisition and processing enable an unprecedented acquisition and processing rate of 750,000 waveforms per second, and the high-precision digital trigger catches the smallest signal anomalies.

The R&S®RTO2000 Series oscilloscopes are another useful alternative. Offering bandwidths from 600 MHz to 6 GHz, these oscilloscopes excel at testing in both the time and frequency domains. With excellent signal fidelity, responsiveness of 1M waveforms/sec, and up to 16-bit vertical resolution, they enable quick measurements and greater confidence.

6 Looking to the Future

American author Samuel Clemens, better known as Mark Twain, was neither a physicist nor a computer scientist, but he remains infinitely quotable. In this case, his perspective on history seems appropriate: "History doesn't repeat itself, but it often rhymes."

In the context of quantum computing, the intertwined histories of transistors, semiconductors, classical computing, supercomputing, and software -- spanning 80 years and counting -- may hint at the path forward for quantum. Over the coming decades, it seems likely that a gradual ascent towards greater availability will expand into a growing number of specialized applications centered on natural systems.

Moving forward, serious research will continue to benefit from serious tools -- and the best tools enable researchers to spend more time focusing on their work. That's how real progress can be made. To that end, the R&S catalog of exceptional test and measurement tools embodies our desire to encourage and enhance present and future research in quantum computing and beyond.

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