Leaflet

Anritsu Advancing beyond

Enabling Quantum Computing: from Design to Test

AnaPico of Switzerland

Anritsu EMEA has partnered up with **AnaPico AG,** creating a comprehensive offering of **RF and Microwave Solutions dedicated to Quantum Computing**: from qubits design to final deployment.

Highlights

Solutions for different Quantum Computing lifecycle stages

- Quantum Materials Research and Development
- Test and Validation of qubit processor chips
- Building and Testing a Quantum Computer
- Scaling-up the number of qubits

Anritsu

✓ **Rubidium™ MG362x1A** RF/Microwave Signal Generator delivering the best phase noise, signal purity, and frequency stability in the market.

✓ **VectorStar™ Vector Network Analyzer**, for unmatched performance in the investigation of materials and in broadband device and model testing.

✓ **ShockLine™ multiport or modular Vector Network Analyzers**, for accurate and scalable system calibration and characterization.

✓ **Signal / Spectrum Analyzers** with Real-Time, Wide Bandwidth, High-Sensitivity.

AnaPico

✓ **APMS / APVSG-X** scalable multi-channel phase coherent Analog and Vector and Signal Generators.

✓ **APPH Phase Noise Analyzer** to characterize the purity of custom-built LOs.

Classic Computers vs Quantum Computers

Classical computers and supercomputers use digital bits to process information and perform computations. Digital bits can be in a 0 or 1 state. The key difference in Quantum Computing is the building block: Quantum Bits, also known as Qubits. Unlike digital bits, qubits can exist in a superposition of states and simultaneously be in a 0 and 1 state, disrupting the classical computations constrains and enabling completely new application scenarios before not even conceivable.

RF and Microwave Challenges in Quantum Computing

A typical quantum computer works in a closed-loop mechanism (Figure 1): generation of control and modulation signals, application of these to the qubits, continuous readout out of qubit status, analysis of the readout signals, and decision-making on what modulation / control signals to apply next, and so on. The typical qubit lifetime is approximately 100 us, so the feedback loop needs to operate with tough low latency requirements, typically < 1 us from readout to qubit control. Each instrument / function block in the loop must therefore operate as fast as possible.

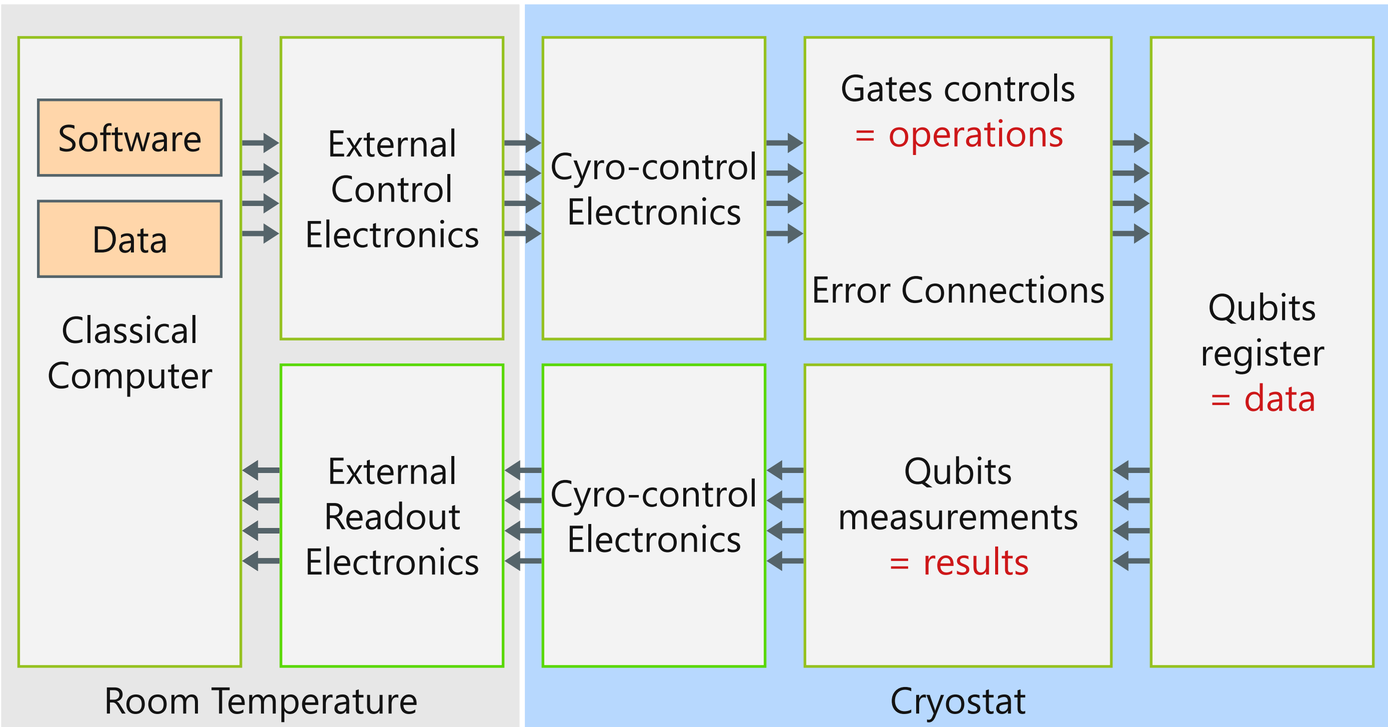


Figure 1: *block diagram of a typical Quantum Computer, including building blocks and signal flow.*

One key challenge pertaining the design of qubits is the research and development of device models and materials to be adopted. Once model and materials have been optimized, the next challenge is engineering and controlling the designed qubits. The manipulation and control of qubits' energy states is achieved using complex nanoseconds-long electromagnetic pulses between 2 and 40 GHz. Using superconducting qubits is one of the most widely adopted approach to build a quantum computer. The quantum processor is located at the bottom of a cryostat (Figure 2), at temperatures as low as 10 mK. A big challenge is ensuring good connectivity to the chip while minimizing crosstalk and other errors. At the top of the cryostat, at room temperature, the focus in on system level performance, stability, synchronization, and, as the number of qubits increases, scalability. The qubit control system is connected to the processor through a high number of RF cables running up and down from the top of the cryostat. Attenuators and filters are used at different temperature stages of the cryostat both to minimize the heat through the cables and to reduce noise. The cryostat RF paths often also include amplifiers and circulators, to improve the signal-to-noise ratio (SNR) and to shorten measurement times. There are several cables per qubit for control and readout. Creating a 50 qubits system requires more than 120 cables. All these RF components and paths must be calibrated so that, at overall system level, the focus is on having the best possible SNR, excellent phase noise, and low latency.

RF and Microwave Test Equipment used in a typical Quantum Computer

Figure 2 shows how RF and Microwave test equipment is integrated in a typical quantum computer. Test solutions are placed at the top of the cryostat, as they operate primarily at room temperature. Quantum Computers include many RF paths, each equipped with several active and passive components. A big source of error is represented by systematic errors. Test and measurements world lends itself well in terms of stimulus and response, which in the quantum world are referred to as a control and readout. Systematic errors are well known in the RF world and removable through well-established VNA based vector error correction calibrations. Given the high number of RF channels / paths included in a typical quantum setup, a multiport or modular VNA are ideal to optimize the calibration.

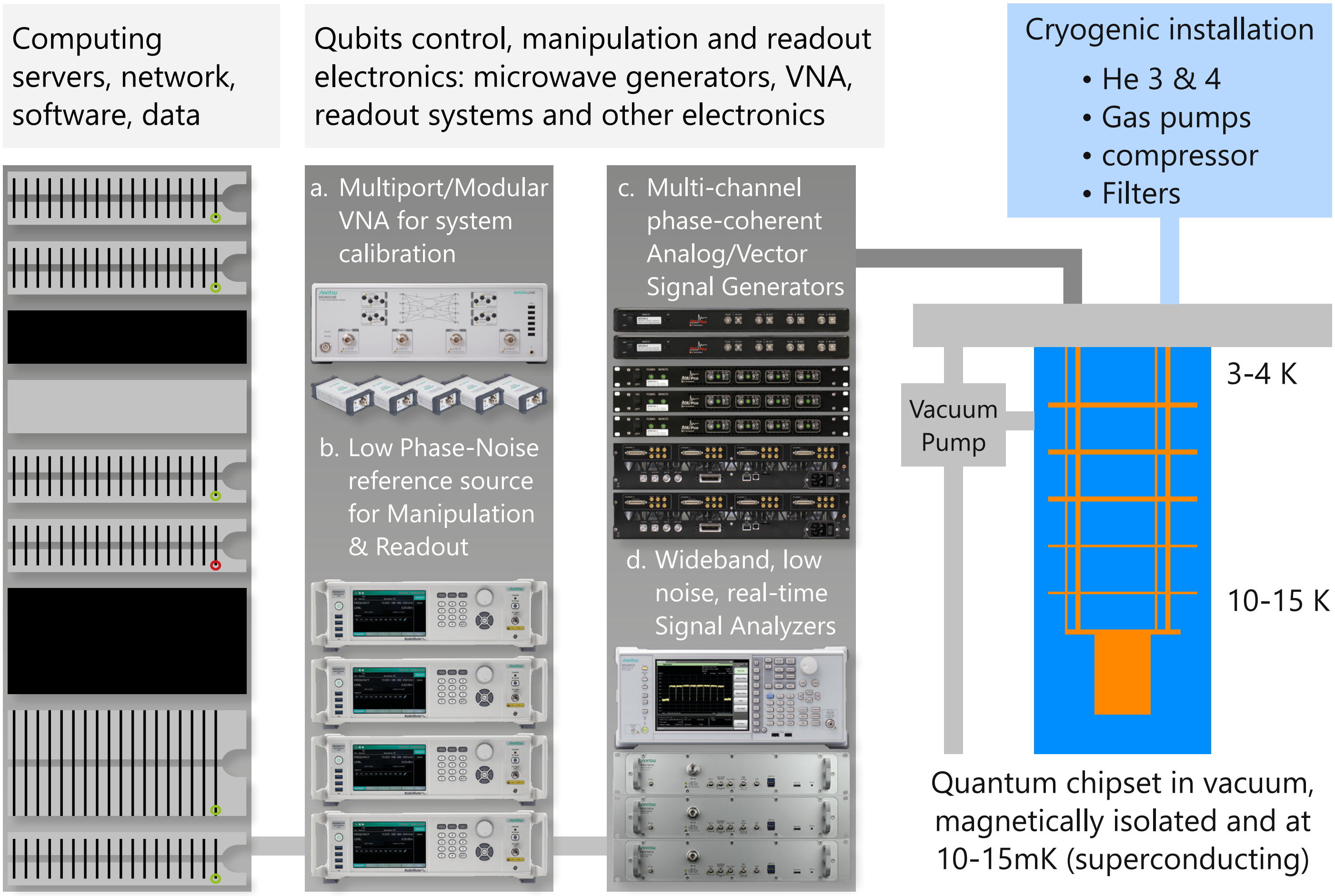


Figure 2: *: Control, Manipulation/Readout and Calibration electronics in a typical Quantum Computer. a) Multiport (Anritsu Shockline™ MS46524B) and Modular (Anritsu Shockline™ MS46131A) Vector Network Analyzers for systematic error correction; b) Anritsu Rubidium™ MG362X1A ultra-low phase noise and high-stability Signal Generator as reference for Manipulation and Readout; c) AnaPico Multi-Channel phase coherent Analog (APMS) and Vector (APVSG-X) Signal Generators for Manipulation and Readout; d) Anritsu MS2840/50A wide analysis bandwidth and low noise Signal Analyzers, and low-latency rackmount Remote Spectrum/Signal Monitor MS2720xA.*

Because qubits are stimulated by microwave pulses in the 2 to 40 GHz range, often up-converters and down-converters are involved to do the qubit control. Here, Analog and Digital Signal Generators are acting as Local Oscillators (LO) for up- and down-conversion stages or used to drive the amplifiers in the chain. The stimulus signal is typically generated with a Vector Signal Generator (VSG) either internally I/Q modulated or externally via an Arbitrary Waveform Generator (AWG). AWG are sometimes used also to provide a single-sideband modulation and drive a qubit at a frequency different from the carrier frequency provided by the VSG. The tones required for qubit read-out are generated in the same way, and all resulting carriers are combined before entering the cryogenic refrigerator. Because qubits are very sensitive to phase noise, the analog and vector signal generator providing the manipulation signals must excel in output signal purity. Wideband and real-time spectrum analyzers, as well as phase noise analyzers, are used to characterize the quality of generated signals.

Key RF and Microwave Signals in a Quantum Computer

Single qubit manipulation:

1. (Shaped) pulse (baseband) signals modulated on RF / microwave frequency. The required modulation pulse can be < 10 ns, posing strict requirements in terms of sampling rate for the pulse generation (> 1 GS/s). The LO RF or microwave frequency is between 2 GHz and 40 GHz. From a pure quantum-physics perspective, the higher the frequency better, because the qubits energy state difference becomes larger. Unfortunately, this also means a more expensive experimental setup. Low phase noise and high spectral purity are required for low-error-rate state detection. Fine phase adjustment and coherency among oscillation signals are both extremely valuable capabilities, as they significantly help lowering the loop latency.
2. Intermediate Frequency (IF) signals (typically < 100 MHz) modulated on (the same) RF / microwave frequency.
3. DC pulse signals for gating / switching function

Readout of qubit state:

- Signals from the cryostat are down-converted to baseband and then to digital domain. Before sending the qubits state info to the Control Board and quantum algorithm software, the digital signals are often pre-processed as much as possible, reducing the data processing load of the control board.

Control and feedback loop:

- The Control Board receives and further analyzes the detected qubits status signals and gives instructions to the qubit manipulation circuitries / instruments about the next modulation schemes.

Challenges Quantum Computing Entails from a RF and Microwave Hardware Perspective

Figure 3 and Table 1 show the main Quantum Computing Challenges, and how Anritsu / AnaPico RF and microwave solutions offer unique benefits to overcome them.

One key challenge pertaining the design of qubits is the research and development of device models and materials to be adopted. Once model and materials have been optimized, the next challenge is engineering and controlling the designed qubits. The manipulation and control of qubits' energy states is achieved using complex nanoseconds-long electromagnetic pulses between 2 and 40 GHz. Using superconducting qubits is one of the most widely adopted approach to build a quantum computer. The quantum processor is located at the bottom of a cryostat (Figure 1), at temperatures as low as 10 mK. A big challenge is ensuring good connectivity to the chip while minimizing crosstalk and other errors. At the top of the cryostat, at room temperature, the focus in on system level performance, stability, synchronization, and, as the number of qubits increases, scalability. The qubit control system is connected to the processor through a high number of RF cables running up and down from the top of the cryostat. Attenuators and filters are used at different temperature stages of the cryostat both to minimize the heat through the cables and to reduce noise. The cryostat RF paths often also include amplifiers and circulators, to improve the signal-to-noise ratio (SNR) and to shorten measurement times. There are several cables per qubit for control and readout. Creating a 50 qubits system requires more than 120 cables. All these RF components and paths must be calibrated so that, at overall system level, the focus is on having the best possible SNR, excellent phase noise, and low latency.

RF & Microwave Solutions for Quantum Computing: Design, Calibration, and Measurements

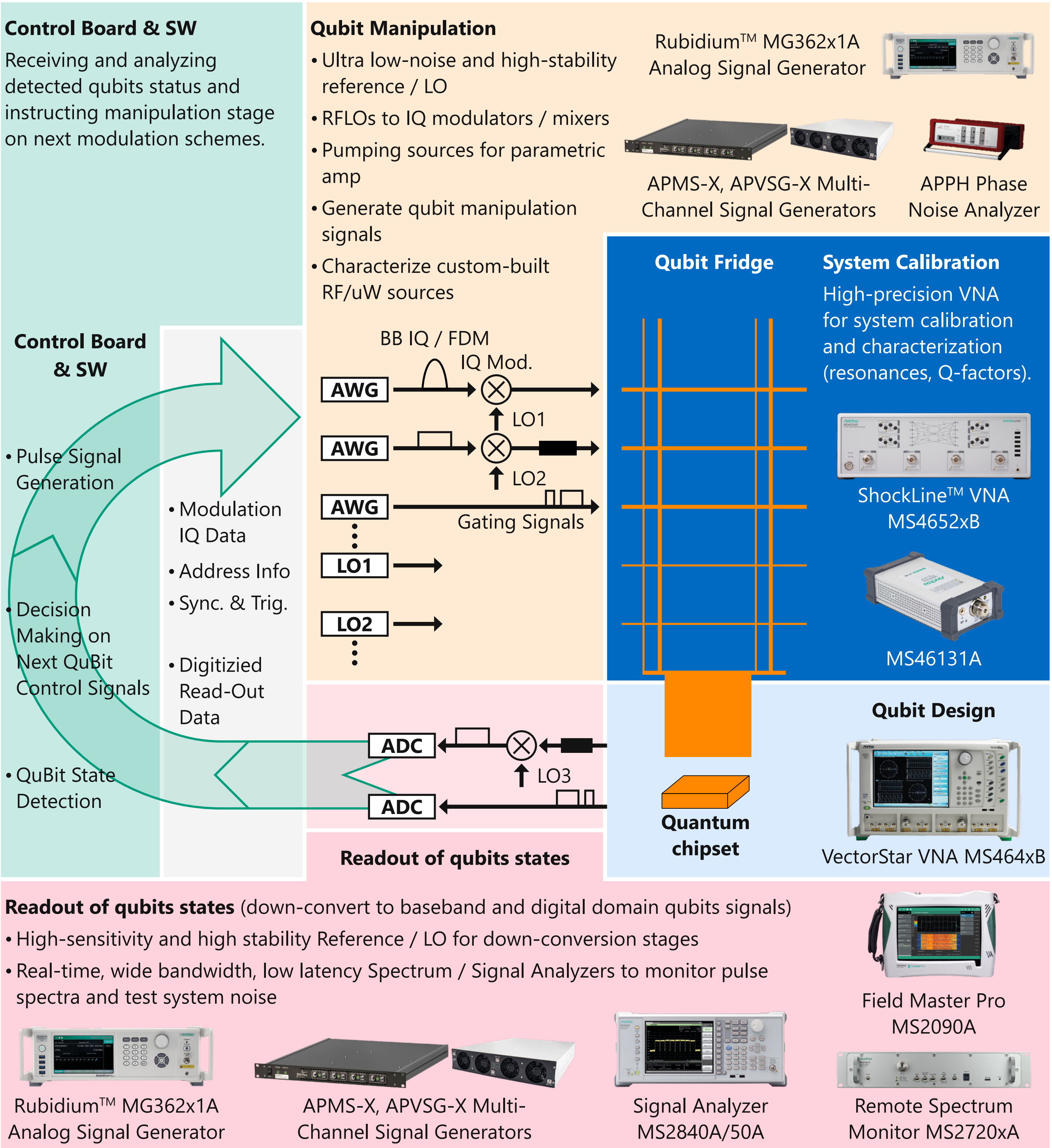
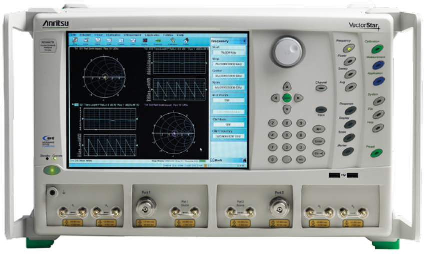
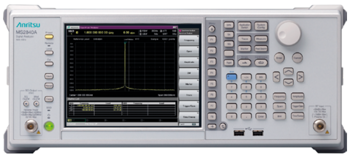


Figure 3: Anritsu / Anapico RF and Microwave Solutions for Quantum Computing: from quantum chipsets design to system calibration and operation.

Table 1: Quantum Computing Challenges and related Anritsu / Anapico Solutions and Benefits.

Challenge	Solution	Benefit
Qubit design and test of materials and device models Test newly designed qubit chips and coherence times of new fabrication runs by: • Testing harmonics and spotting undesired resonant frequencies • Broadband characterization (e.g. 70 kHz MHz to > 70 GHz) • Running two-tone measurements to assess qubits' resonances and Q-factors	Anritsu VectorStar™ VNA 	Industry leading performance and 9 kHz to 220 GHz broadband frequency coverage for R&D on qubit design, model validation, materials testing, and to characterize the resonant frequencies of quantum processors. Ideal tool to assist in debugging individual quantum computing chips and help developers run two-tone measurements to quickly determine resonant frequencies and key quality factors of the test chips (mapping the results into the coherence times of the quantum system).
Qubits Manipulation and Readout Manipulate and readout of qubits' energy states using complex nanoseconds-long electromagnetic pulses between 2 and 40 GHz, across multiple phase-coherent channels. To be achieved while: • Maximizing Signal-to-Noise-Ratio (SNR) by enhancing spectral purity and minimizing Phase-Noise • Shortening Measurement Time by reducing latency and switching times • Finely tuning the phase while keeping coherency among oscillation signals • Optimizing system performance, stability, synchronization, and scalability.	Anritsu Rubidium™ MG362x1A Signal Generator 	Unmatched spectral purity, superior atomic grade stability compared to conventional OCXOs, best phase noise in the market (-140 dBc/Hz at 10 GHz, 10 kHz offset). Ideal for high precision LO within the manipulation and readout blocks, as ultra-stable ultra-low jitter clock, and to drive amplifiers.
	Anapico APMS-ULN Multi-Channel Analog Signal Generator 	Multi-Channel Phase Coherent Oscillation Source. Up to 4 fully independently adjustable, phase-coherent and phase memory channels, up to 6, 12, 20, 33, and 40 GHz. Ideal as RF LO to IQ modulators / mixers and as pumping source for parametric amplifiers.
	Anapico APVSG-X Multi-Channel Vector Signal Generator 	Multi-Channel Vector Signal Generator. Up to 4 fully independently adjustable, phase-coherent and phase memory channels, up to 6, 12, 20, 33, and 40 GHz. Ideal as RFLOs to IQ modulators / mixers and to generation qubit manipulation signals.

Challenge	Solution	Benefit
Removing Systematic Errors Systematic errors in qubit state preparation arise due to non-idealities in the qubit control lines such as impedance mismatch. High-precision VNA removes such errors via a system calibration.	[Anritsu VectorStar™ MS464xB VNA] 	4-port integrated VNA with 4 independent sources and 8 receivers.
	[Anritsu Shockline™ Modular VNA MS46131A] 	Unique compact and modular VNA offering multiple parallel 1-port measurements as well as distributed 2-port measurements with > 25 m distance between ports.
Assessing stimulus and readout signals quality Signal / Spectrum Analyzer must have low noise floor to characterize system Signal-to-Noise-Ratio (SNR) and wide real-time analysis bandwidth to monitor and characterize qubit state pulsed readout signals.	[Anritsu MS2840A Spectrum / Signal Analyzer] 	Ultra-low noise Spectrum/Signal Analyzer, enabling verification of overall system noise, amplifiers' performance and of the detection setup, as well as measuring and calibrating I/Q mixers.
	[Anritsu MS2850A Spectrum / Signal Analyzer] 	Spectrum/Signal Analyzer with up to 1 GHz wide analysis bandwidth. Wide bandwidth and low noise floor are a must when analyzing IQ modulated pulsed signals in the readout chain, and for monitoring pulse spectra.
	[Anritsu MS2720xA Remote Spectrum Monitor] 	Low-latency remote Spectrum/Signal Analyzer, with 110 MHz real time analysis bandwidth.
	[Anritsu MS2090A Handheld Spectrum Analyzer] 	Premium Real-Time handheld Spectrum Analyzer with 110 MHz wide analysis bandwidth. Signal quality assessment and troubleshooting solution. Thanks to its form factor, sensitivity, and real-time capabilities, it is an incredibly valuable tool when having to detect undesired sidebands, or short and sporadic interference signals.
Characterizing custom-built Local Oscillators	[Anapico APPH Phase Noise Analyzer] 	Versatile and broadband signal source analyzer up to 7, 26, 40, 50, 65 GHz, with very high measurement sensitivity.