SOLUTION BRIEF

Quantum Control System (QCS)

The world’s first fully digital quantum control solution

KEYSIGHT

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Keysight's Quantum Control System (QCS) combines dedicated quantum control hardware and full-stack software capabilities to provide an easy-to-use solution for control and readout of quantum devices. QCS is a direct digital conversion (DDC) architecture for the generation and acquisition of microwave, baseband, and digital signals used to control and read out quantum devices.

The new quantum specific Python API is a powerful and intuitive software that enables easy execution of textbook quantum experiments, the flexibility to quickly design and execute custom pulse sequences, all while automatically ensuring timing and synchronization to sub-nanosecond levels. Leveraging the on-board FPGAs is simple and intuitive via the Python API. It facilitates dynamic user defined pulse primitives and real-time heterodyne demodulation, allowing the user to focus on quantum physics rather than FPGA programming.

Highlights

- Full DDC and acquisition of microwave, baseband, and digital signals used to control and read out qubits.
- Simple-to-use API and GUI interfaces give quick access to textbook quantum experiments and custom pulse sequences.
- Tight integration between hardware and software to provide a complete control and readout solution.
- Advanced clock distribution and timing software ensures phase and event synchronization across all channels in the system.

Software

The primary software interface for the quantum control system is through a quantum-specific Python API. This API allows users to easily program sequences representing simple qubit experiments, complex quantum algorithms, or anything in between using a simple and intuitive syntax. Additionally, a graphical user interface (GUI) use model is included to provide a visual interface for simple experiments and general lab control.

QCS API

The QCS API simplifies the user experience by allowing users to jump directly into the design and execution of quantum experiments after a simple initial configuration. It consists of the following main components.

Quantum Configuration to define the mapping between QCS hardware and quantum objects (such as qubits, couplers, and readout resonators). Once set up, this configuration allows for the automatic configuration of the experiment without user input regardless of the specific quantum sequence or the experimental parameters. In addition, this configuration includes the connectivity map of the quantum circuit.

```
TunableQubit qubit1:
    AnalogChannel xy:
        instrument: awg1x4
        channel_number: 2
    readout: readout1
```

Figure 1. Static System Configuration Syntax

QCS API to define sequences of pulses or calibrated gates (see below) on any number of qubits supported by the QCS configuration. Users can define any type of two-qubit gate (e.g., baseband or microwave) that is compatible with the connectivity specified above. In addition, pulses parameterized to enable fast sweeps of the circuits. The combination of sequences and sweeps fully describe an experiment, which can be run from a Python script or Jupyter notebook. Examples of standard sequences (e.g., T1, Ramsey, dynamical decoupling) sequences will be included for reference, and arbitrary sequences are programmable through the API.

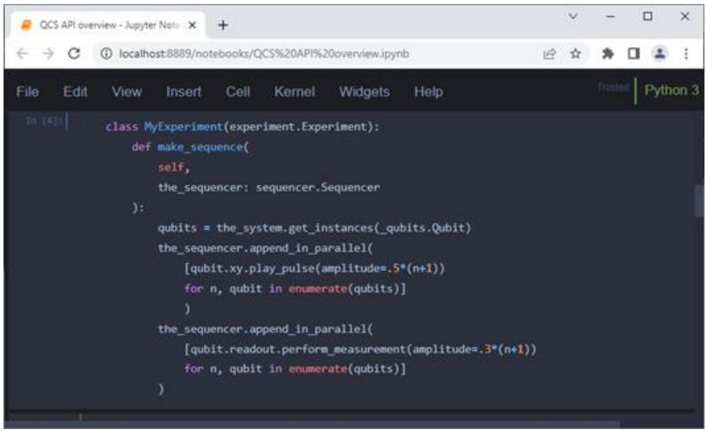

Figure 2. Quantum-Specific Python API

Device Calibration Manager to manage the pulse parameters for each of the calibrated gates. Accessible through the Python API, it provides information on the current and past parameter values, facilitating the comparison between similar measurements taken at different times, or between multiple devices.

Waveform and Data Visualization Tools to preview waveforms and pulse sequences before executing them on hardware, and to view a graphical representation of the results of qubit measurements.

Figure 3. QCS Data Visualization

Software package

The QCS software includes multiple products to provide a complete solution for quantum systems. Some of these products require one license per system (one per host PC), and others run on the hardware itself requiring one license per modular instrument in the system. The correct type and number of licenses are assigned when ordering or upgrading quantum control systems from Keysight and can all QCS software be easily installed and upgraded together using the PathWave Test Station Manager. The table below shows the software included with the QCS.

Table 1. Software licenses included with the quantum control system

QCS Software Licenses

Feature	Description	Licensing
M5401LUNA	Labber Quantum Software License	1 per system
KS2201A	PathWave Test Sync Executive License	1 per modular instrument
KF9001B	PathWave FPGA Run-Time License	1 per M5300A or M5200A
M5400B	Quantum FPGA IP Library for M5xxx Control Hardware	1 per M5300A or M5200A

Hardware

The Keysight QCS hardware is based on the M5000 series high-performance PXI series of modules that were designed using proprietary Keysight technology specifically for quantum applications.

Analog LOs and mixers in traditional hardware used for quantum control require frequent calibration, introduce leakage noise, and contribute to slow drifts in the performance of the system. The Keysight QCS hardware fully eliminates the need for these components leading to enhanced ease-of-use, unrivaled noise performance, and improved long-term stability.

The figure below shows the contrast between a traditional baseband IQ architecture and our next generation fully digital solution with digital up conversion (DUC). Note that instead of the drift-prone and error-prone components of the traditional approach, the DUC approach uses a digital application-specific integrated circuit (ASIC) to provide a precise and consistent output.

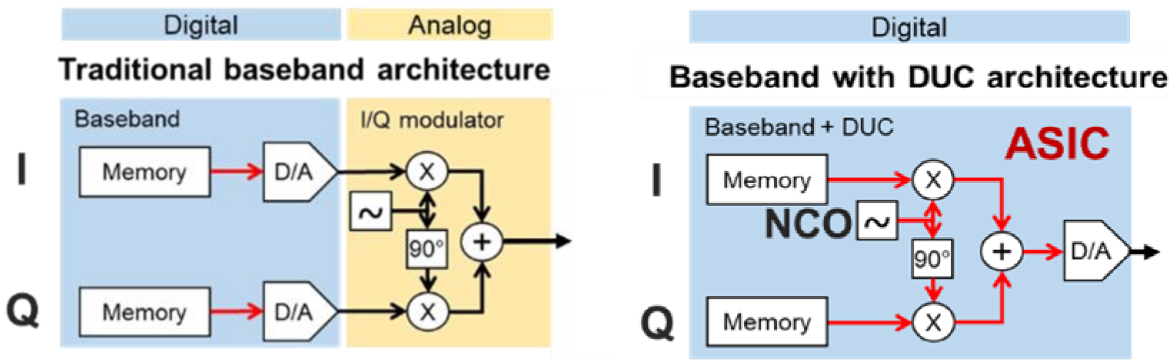

Figure 4. Traditional I/Q upconversion (left) compared with digital upconversion (right)

Table 2. Hardware products in a quantum control system

QCS Hardware Product Overview

M5200A	PXIe High-Speed Digitizer 4 Channels, 2 GHz BW, 4.8 GSa/sec, 12-bit, 1 GSa/ch memory
M5201A	PXIe Down Converter 4 Channels, 2-16 GHz RF, 0.2-2.2 GHz IF, Integrated IO
M5300A	PXIe RF Arbitrary Waveform Generator 4 Channels, DC-16 GHz RF, 2 GHz IF, 14-bit
M5302A	PXIe Digital I/O 28 LVDS Channels, 8 Trigger Channels
M9046A	18-Slot High-Performance PXIe chassis
M9032A	System Sync Module, 2-port
M9033A	System Sync Module, 5-port

M5300A RF AWG

The M5300A is a two-slot PXIe module with four high-speed AWG outputs, clock input and output, and eight triggers. It supports four directly synthesized RF channels with up to 16 GHz of RF and 2 GHz of instantaneous bandwidth.

The M5300A provides a waveform memory per channel of 1GSample – half real (I) samples and half imaginary (Q) samples.

Powerful clocking technology ensures tight phase synchronization with:

- All output channels of the module
- Output channels of additional M5300A modules in the system
- Input channels of the M5201A frequency down counter (see (below)

Figure 5. M5300A RF AWG

Table 3. M5300A output characteristics

M5300A Output Characteristics

Resolution	14-bits
Signal bandwidth	2 GHz
RF output	0 to 16 GHz
Output power	-2 to 0 dBm
Output impedance	50 ohms
Waveform memory per channel	1 GSa (500 MSa I and 500 MSa Q)

M5200A High-Speed Digitizer

The M5200A is a single-slot PXIe four-channel high-speed analog to digital digitizer. It supports four 2 GHz channels with 4.8 GSa and 12-bits of resolution for high-definition sampling in quantum computing applications.

Figure 6. M5200A High-Speed Digitizer

Table 4. M5200A input characteristics

M5200A Input Characteristics	
Number of channels	4
Sampling rate	4.8 GS/s
Resolution	12-bit
Impedance	50 Ohm
Bandwidth	2 GHz
Memory depth	1 GSa/Ch

M5201A Frequency Downconverter

The M5201A is a single-slot PXIe low-IF downconverter module with four pairs of RF/IF channels and a single, shared, internal local oscillator (LO). The RF input frequency range is 2 to 16 GHz. The intermediate frequency (IF) ranges from 10 MHz - 2400 MHz.

The clock generator on the M5201A provides a reference which is then used to generate the Local Oscillator (LO) frequency required for the application. Inputs to the clock generator include the front panel 2.4 GHz clock input and the 100 MHz PXIe clock and DSTAR clock from the chassis. When used with the M9046A chassis, the 2.4 GHz clock provides minimal phase noise and drift.

Figure 7. M5201A Frequency Downconverter

Table 5. M5201A channel characteristics

M5201 Channel Characteristics	
RF input characteristics	
Frequency range	2 GHz to 16 GHz
Max Input power	0 dBm
IF output characteristics	
Bandwidth	10 MHz - 2400 MHz
SFDR	50 dBc
Output Power	1 dBm
LO characteristics	
Frequency Range	1 GHz to 18 GHz

M5302A Digital IO

The M5302A is a single-slot Digital IO PXIe module with 28 programmable LVDS channels and 8 single-ended channels. The LVDS channels can be used to communicate to the device under test or can be used to control other devices by emulating protocols. The single-ended channels are suitable for event triggers or other general-purpose IO applications.

There are 28 bidirectional differential channels included on a 100-pin, front panel connector. These differential signals are LVDS (meant to drive 100-ohm differential load) and have a 1.2 Gbps maximum toggle rate. The Dig connector also includes +5 V power that is available to the user to power external interface circuitry (maximum current load is 0.5 A).

Eight SMBs are available for instrument triggers or other general purpose I/O signals. These channels are single-ended with a voltage swing of 0 – 3.3 V when driving High Impedance loads (the voltage levels at the DUT are halved when connected to a 50 Ω load).

Figure 8. M5302A Digital IO

Table 6. M5302A channel characteristics

M5302 Channel Characteristics	
LVDS Channels	
Channel type	Differential, Bidirectional
Number of channels	28
Channel impedance	100 Ω differential (nominal)
Maximum output channel toggle rate	1.2 Gbps
Maximum input channel toggle rate	1.2 Gbps
General Purpose Trigger Channels	
Channel type	Single-ended, bidirectional, ground reference
Maximum output channel toggle rate	150 MHz
Maximum input channel toggle rate	75 MHz

M9032A/M9033A System Synchronization Module

The M9032A PXIe System Synchronization Module is a single-slot, 2-port module that provides multi-module and multi-chassis synchronization and triggering for Keysight's quantum control systems.

The M9033A PXIe System Synchronization Module is a dual-slot, 5-port module that provides the same functionality and allows multi-chassis systems to scale in a star configuration.

Both modules contribute to the synchronization and clock alignment of the M5000 modules in the system, and one is required for each chassis in the QCS.

Figure 9. M9032A System Synchronization Module

M9046A 18-slot PXIe Chassis

The M9046A 18-slot PXIe chassis delivers the power and cooling required for high-performance QCS hardware.

The PXIe Gen 3 backplane provides up to 24 GB/s system and 8 GB/s slot-to-slot communication speeds ensuring fast load times, and the innovative chassis cooling system with increased volume of airflow improves per-slot cooling and lowers acoustical noise in the system.

Additionally, the -QS1 model of the chassis includes an embedded 2.4GHz reference clock and splitters, enabling distribution to all M5000 cards for optimal phase noise performance.

Figure 10. M9046A 18-slot PXIe Chassis

Synchronization Example

Beyond individual module performance, quantum control requires tight coordination and synchronization between the different modules in the system. The QCS uses powerful clock alignment technology to ensure that all modules in the system maintain tight phase and event synchronization. To demonstrate this, we demonstrate results from the following setup (Figure 12): Two signals at 6 and 8 GHz are generated by separate M5300A AWG modules. Both signals are downconverted by an M5201A frequency downconverter and read out on an M5200A digitizer. The phase difference between the two signals is measured and plotted as a histogram over 8 hours of measurement. The results demonstrate excellent long-term phase stability, with all counts within 0.5 degrees.

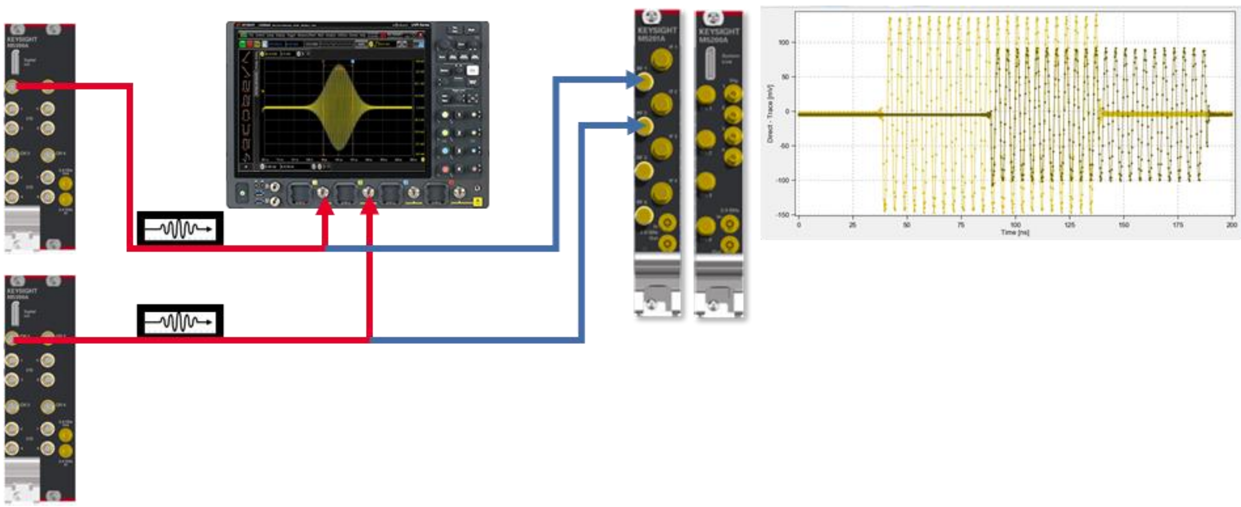

Figure 11. Precise phase alignment of signals in a QCS, example measurement setup

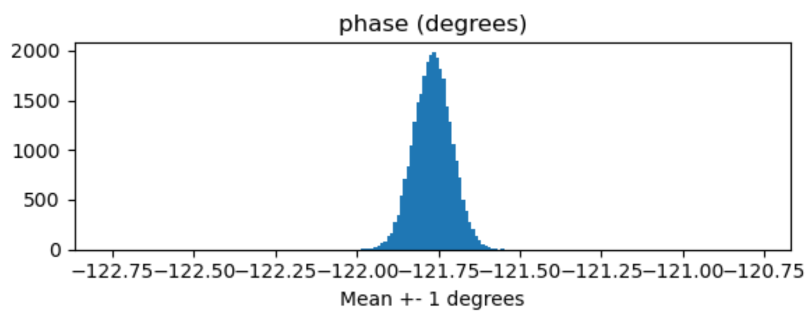

Figure 12. Histogram of phase difference between two different M5300A AWG modules over 8 hours

Conclusion

Keysight has designed a next-generation solution for control and readout of quantum systems. By providing a quantum-centric API and eliminating the need for traditional IQ calibration, the Keysight quantum control solution is extremely easy to use. We have leveraged our rich history as leaders in RF and microwave technology to provide unrivaled performance in stability and phase coherence, and the full system has been designed to seamlessly scale as your system grows.

For more information on Keysight Technologies' products, applications, or services, please visit: www.keysight.com