Holzworth

QUANTUM SOLUTIONS GUIDE

1. The Qubit Conversation

Wikipedia defines Quantum Computing as "the exploitation of collective properties of quantum states, such as superposition and entanglement, to perform high speed computations of large and complex datasets". Original quantum computing concepts were being proposed in the early 1980's and by the 1990's quantum algorithms were being introduced. In the last decade, incredible investments and development efforts have been allotted to quantum computing by universities, companies, and governments; all racing to reach Quantum Supremacy.

There are many approaches being taken to overcome the challenges of optimizing the quantum computing function with the most common approach currently being that of the superconducting quantum circuit, which relies on the qubit (Quantum Bit). Unlike a classical computing bit that is generated by transistor logic gates and can reside only as a 1 or a 0, the qubit can be in a state of 1 or 0 or in a linear combination of both states, which is enabled by the superposition phenomenon.

Superposition is commonly demonstrated via the Bloch sphere as shown in Figure 1. The superposition of a qubit is indicated by a vector having specific angles from both the z-axis (θ) and the x-axis (Φ). The 1 state is represented by the south pole of the sphere, while the 0 state is represented by the north pole. A qubit in superposition, is represented by a vector pointing to a location on the spherical surface that lands anywhere between the two poles.

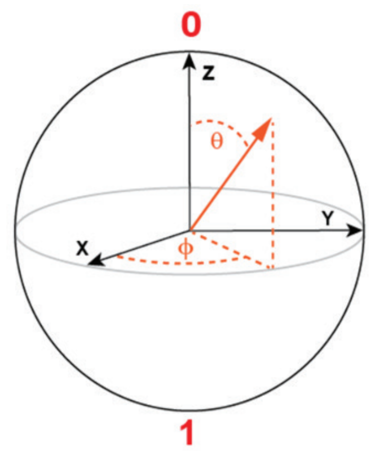

Figure 1: Bloch Sphere

In addition to superposition, entanglement is a critical factor in putting qubits to work as they behave randomly. Individual qubits do not offer advantages over classical computing bits. Qubits must work together in order to exist within a single, coherent quantum state so that they can "talk". Changing the state of one qubit within an entangled pair will instantly and predictably change the state of the second qubit.

Generating qubits is challenging, but this is not the gating factor as superconducting quantum chipsets can currently generate more qubits than can actually be put to use. Maintaining a coherent relationship between qubits via superposition and entanglement for greater periods of time is necessary for implementing these quantum computing systems into more and more practical applications for solving real world problems.

2. The Quantum State

Both superposition and entanglement are necessary to create coherency between qubits so that they can effectively operate in the quantum state. However, qubits are fragile and their operating environment can cause decay from the quantum state, referred to as decoherence, which unfortunately occurs after only a few hundred microseconds of achieving coherence. System noise, caused by mechanical vibrations and/or heat can cause a loss of superposition, resulting in errors before computations are complete.

To help isolate qubits from noise, the quantum processor is located at the bottom of a multi-stage, supercooled chamber (dilution refrigerator) where temperatures approach zero Kelvin.

The image in Figure 2 (credit Twitter @ibmreseach) shows IBM's Q quantum computer with an open dilution refrigerator exposing the "chandelier", which is the brass-colored hardware hanging in front and center of the image. The chandelier is composed of superconducting coaxial cables, cryogenic isolators, quantum amplifiers, an abundance of shielding and much more (to the sum of greater than 2000 components), all in an effort to maintain the quantum state of the fragile qubits for as long as possible.

Figure 2: IBM Q - Quantum Computer

Increasing the number of coherent qubits and the amount of time these qubits can reside within quantum state is what makes the quantum computer an incredibly powerful tool. Unlike a classical computer, a quantum computer can handle parallel increases exponentially as more and more qubits are added to the system:

N qubits = 2^N bits

Given this formula, it has been theorized that a quantum computer with 300 qubits could perform more simultaneous calculations than there are atoms in the entire universe. That is powerful. However, the current record for maximum operating capacity of a superconducting quantum system is 72 qubits, set by Google in 2018.

3. Phase Coherent RF Signals

Referring to the IBM Q system image in Figure 2, superconducting quantum computers can contain several racks of commercially available MW/RF test equipment. One important task for this test equipment is to generate precise microwave pulses, which are used to manipulate qubits into superposition while also maintaining entanglement. These microwave pulse signals are also tasked with measuring the output data that is generated by the qubits.

The microwave control pulses (inputs) are routed into the dilution refrigerator with cautious handling to prevent disruptive noise from interfering with the qubits at the quantum processor. The measurement pulses (outputs) are reflected back from the readout resonators and routed out of the dilution refrigerator to the microwave equipment to be downconverted and digitized so that a classical computer can then process the data.

Quantum computing systems designers are experimenting and implementing different approaches for generating these microwave control/measurement pulses. A popular method used in superconducting quantum circuits is to combine the pulsed waveforms generated by an ARB (Arbitrary Waveform Generator) with a spectrally pure and highly stable RF sinusoidal carrier signal. More simultaneously pulsed control/measurement signals are required as more qubits are being introduced and utilized by these systems.

As quantum computing system designs mature, the requirements for the number of stable, independent control/measurements signals within a system are increasing. Precise manipulation of qubits and longevity of their quantum state requires not only the absolute phase stability of a control/measurement signal, but also relative signal-to-signal phase stability of all the integrated RF signal sources. This relative phase relationship between signal sources is commonly referred to as phase coherency.

4. Optimizing Phase Coherency

Two sinusoidal signals are phase coherent if they have a constant relative phase. Having a constant relative phase does not dictate that these signals must be of the same frequency and phase, but that there are no variations from their initial relative phase relationship. Therefore, two signals generated at different frequencies can exhibit phase coherency if their phase rotations maintain the same relative rates. However, real world electronics and operating conditions do not allow for theoretically perfect phase coherency between RF signals so it must be measured to ensure signal-to-signal phase stability.

Properly measuring the phase coherent relationship between two signals is not as simple comparing them with an oscilloscope. The electronics within the oscilloscope itself will contribute to the overall measured phase deltas, which results in inaccurate data. This would be a non-factor if an acceptable level of phase coherency were to be quantified within milliseconds, microseconds or even nanoseconds. As quantum computing system designs mature the relative signal-to-signal phase stability of the integrated high performance signal sources must continue to approach theoretically perfect phase coherent levels. Attoseconds of phase drift is ideal, but current technology places high performance phase coherency within the realm of femtoseconds. A more accurate method for measuring relative phase stability eliminates a large amount of test system electronics and implements a simple phase detector (mixer) circuit. Figure 3 outlines a typical measurement setup between two signal sources where the relative phase differences are monitored at the IF port as a DC value that will vary with time and temperature.

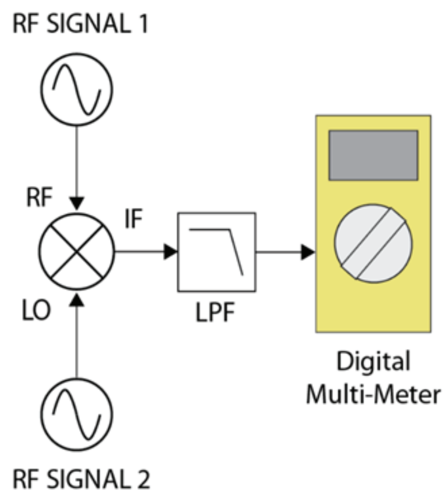

Figure 3: Phase Coherency Measurement Setup

Phase coherency begins with an individual signal source design being optimized for the best absolute phase stability possible, which can be quantified via the phase noise and/or jitter performance of the source's output signal. Once the stand-alone signal source design has been optimized for absolute phase stability, there is yet a higher hurdle to clear in synchronizing two or more of these signal sources so that their relative phase relationships are then optimized.

Synchronizing multiple signal sources (RF synthesizers, signal generators, etc.) is accomplished by utilizing a common reference signal. Using a common reference signal eliminates the independent free running condition of each independent signal source, but this doesn't equate to perfection. In this scenario, not only does the absolute phase stability of each RF signal generator change independently due to varying thermal effects of each stand-alone chassis, but the coaxial cables that are used to route the common reference signal to each signal source can introduce undesired phase shifts due to the thermal effects on the RF cable insulators.

Signal source manufacturers are discovering techniques for improved phase coherency via multi-channel platforms that integrate multiple signal sources within a common chassis. This approach reduces the challenge of managing the varying thermal effects of several independent chassis.

5. Holzworth Performance

Holzworth Instrumentation introduced its first multi-channel RF Synthesizer products in 2008 to support satcom ground station LO applications where channel-to-channel (signal-to-signal) stability is critical. Figure 4 shows an industry first, offering up to 8x independently tunable, 8MHz to 6GHz RF outputs within a single 1U high chassis. As time went on, semiconductor chipset manufacturers began adopting the multi-channel architecture for use in manufacturing ATE (Automated Test Equipment) systems as a more compact and cost-effective solution in lieu of using a series of larger, single channel signal generators. The optimized channel-channel phase stability (phase coherency) was an unexpected and welcomed advantage that eliminated excessive test margins (increasing yields) that were once necessary to account for any relative signal instabilities within the test system.

Figure 4: HS6008A - Original 8x Channel, 6GHz RF Synthesizer

The Holzworth multi-channel RF synthesizer products were originally architected to operate within a 1U high, fanless chassis. The fanless chassis was a key factor for maintaining signal phase stability as chassis fans not only cause microphonics, but fans also push/pull environmental air through the chassis and can create uneven cooling across the internal electronics contributing to unpredictable phase variations across the integrated signal sources (channels). By incorporating a proprietary, all aluminum chassis design, thermal mass became a positive attribute for maintaining signal stability.

5.1 Single Channel Absolute Performance

Figure 5 shows a typical example of the absolute phase stability of a single channel output of a Holzworth Multi-Channel RF Synthesizer at 5GHz. The data demonstrates that approximately 10 to 12 hours of warm up time is necessary for a unit to reach steady state thermal operation in order to provide ideal phase stability. At steady state operational temperatures (>600 minutes), the channel output performs with less than 200 femtoseconds of overall phase drift, which is excellent. However, even at steady state operation, the data displays performance fluctuations that result from the slightest variations in room temperature.

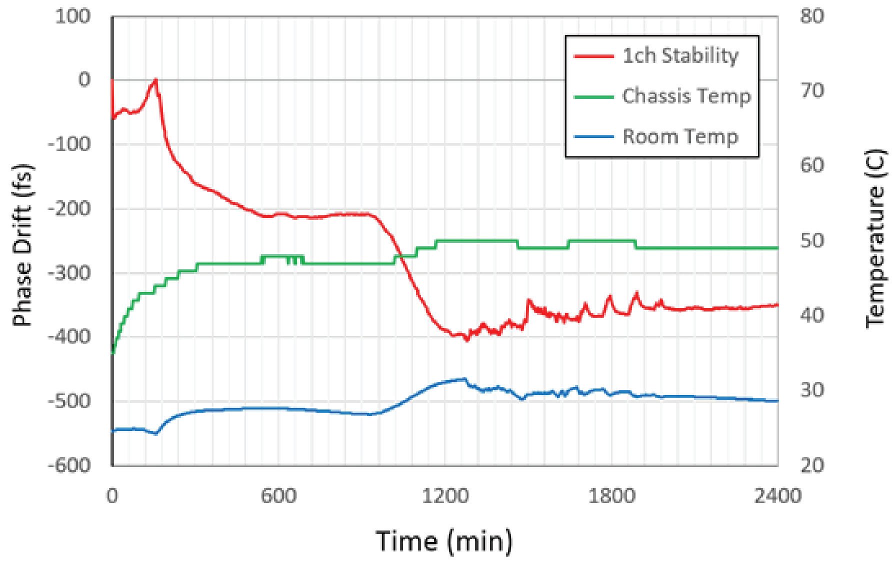

Figure 5: 1 Channel - 5GHz Absolute Phase Stability (40 hours)

5.2 Two Channels (Common Chassis) Relative Performance

In comparing two channels installed within the same chassis, phase coherency testing reveals that the relative phase stability versus room temperature does vary over time. Figure 6 contains a 16-hour snapshot of the relative phase stability of 2 channels contained in the same chassis, operating at 5GHz. The data timeline 0 minutes begins following a 10 hour warm up period.

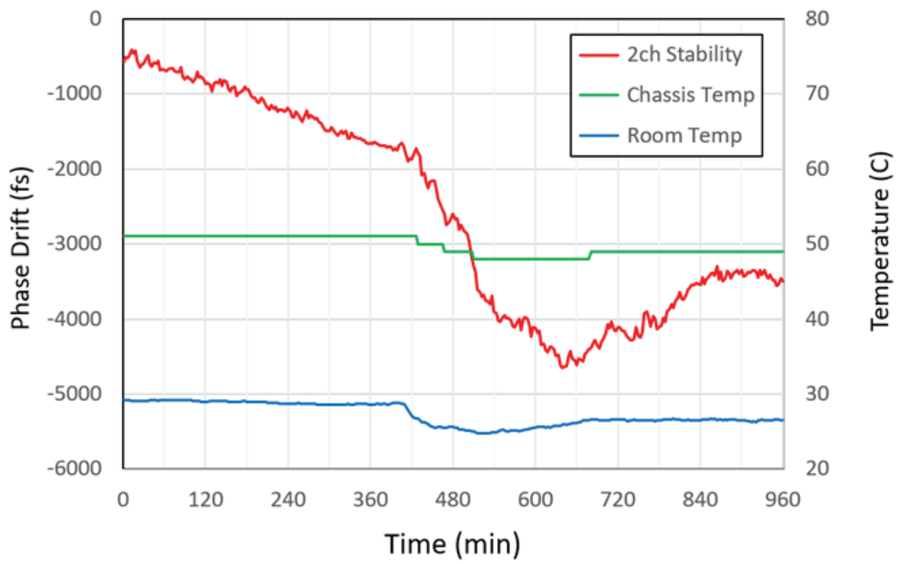

Figure 6: 2 Channels (Common Chassis) - 5GHz Relative Phase Stability (16 hours)

The first 7 hours (≤ 420 minutes) of steady state operation demonstrates an average channel-to-channel relative phase stability that changes by a maximum of 200 femtoseconds per hour, which is very good. At the 7-hour marker the overnight room temperature begins to drop abruptly and the relative channel-to-channel stability degrades to as high as 1.3 picoseconds per hour. Once the room temperature again begins to stabilize, the unit returns to the expected steady state performance.

5.3 Two Chassis Relative Performance

As priorly noted, the negative effects of room temperature changes are further exaggerated when the RF outputs of two separate signal source chassis are monitored. Figure 7 illustrates the post warm up data when comparing the relative phase drift between 2 channels, located in 2 separate chassis that share a common reference signal.

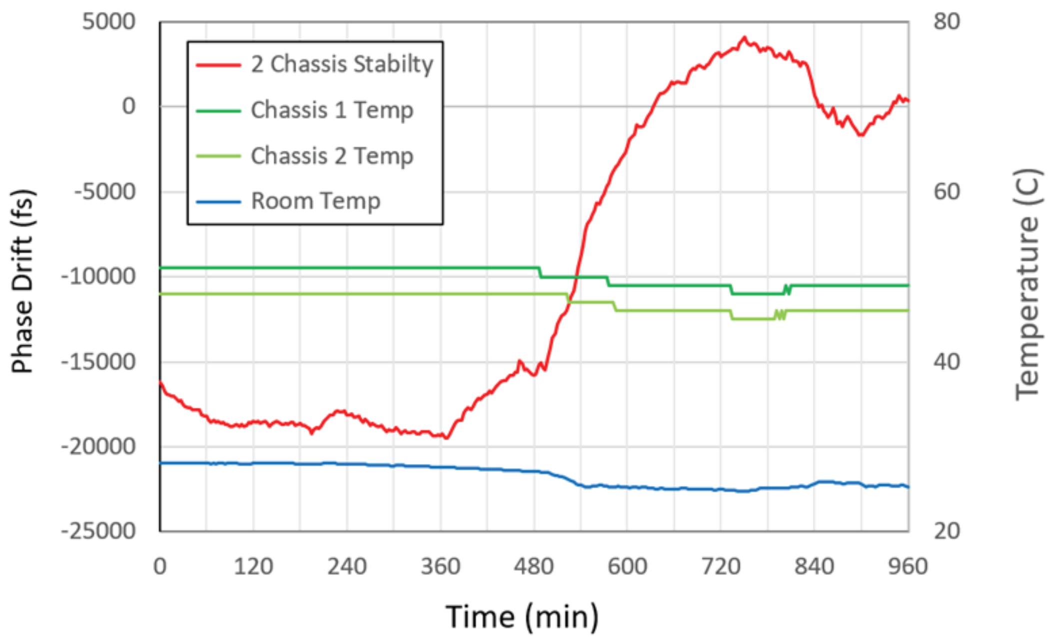

Figure 7: 2 Chassis - 5GHz Relative Phase Stability (16 hrs)

The first 6 hours (≤ 360 minutes) of steady state operation demonstrate a channel-to-channel (chassis-to-chassis) relative phase stability that varies by approximately 150 to 500 femtoseconds per hour, which is still considered to be very good. At the 8-hour marker (480 minutes) the abrupt drop to overnight laboratory temperatures results in a drastic change in the relative channel-to-channel stability to as high as 6.5 picoseconds per hour. Again, once the room temperature stabilizes, the chassis-chassis performance returns to the expected relative phase stabilities.

The data provided here confirms that a tightly controlled operating environmental temperature is key to maintaining the best possible relative phase stability under the various configurations.

6. The Holzworth Advantage

With the original Holzworth Multi-Channel RF Synthesizer products, the current generation of Holzworth HS9000 Series Multi-Channel RF Synthesizers was limited to maximum of 8x broadband channels per chassis. That was sufficient until quantum computing systems designers began making advancements that were rapidly increasing the number of working qubits within a system.

Per the data provided in Section 5, it is evident that the channel-channel phase drift degrade as more and more signal source chassis are added to a system. In response, Holzworth engineering has recently made great strides in increasing the independently tunable channel count within a single 1U chassis.

By implementing application specific, narrowband channels that are limited to 2GHz of tunable bandwidth, Holzworth now has configuration options that allow for up to 32 independently tunable signal sources within a single 1U chassis. Figure 8 is an image of Holzworth model number HS9032B, equipped with 32x independently tunable channels that are tunable from 4GHz to 6GHz (1mHz minimum step size).

Figure 8: Model HS9032B – 32x Multi-Channel RF Synthesizer

This 32x channel configuration not only saves vital real estate within the equipment rack, but the channel-to-channel phase coherency is highly optimized. Figure 9 demonstrates the phase coherency between 2 channels within this system, as measured over a 16-hour period, following a minimum of 10 hours of warm up time.

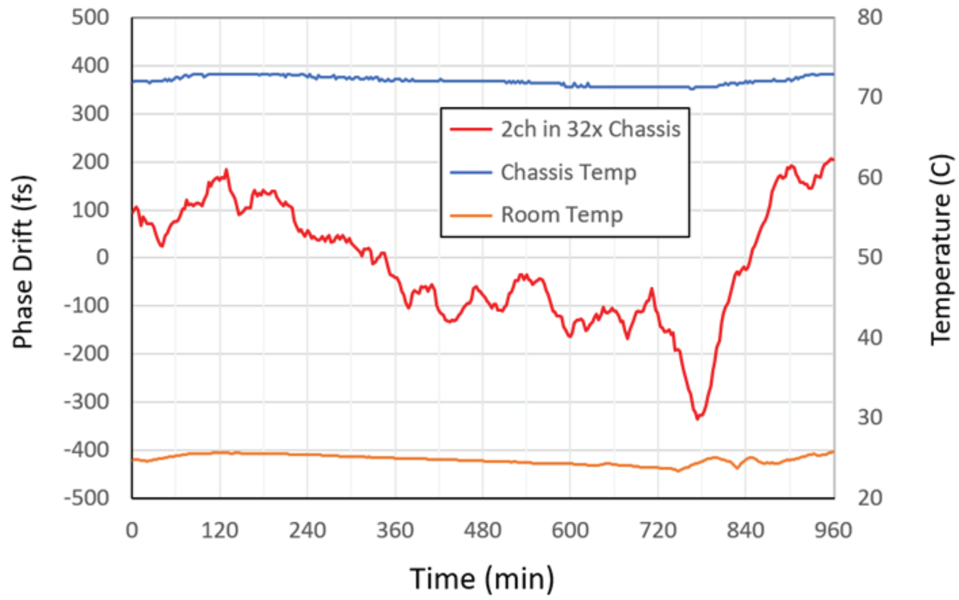

Figure 9: 2 Channels within a 32x Channel Chassis -
5GHz Relative Phase Stability (16 hrs)

Under steady state operating conditions and a relatively consistent room temperatures, the relative channel-to-channel phase drift is maintained at less than 50 femtoseconds per hour. The overall worst case phase drift between channels over the entire 16-hour measurement period does not exceed 550 femtoseconds, which is exceptional. This is 10 times less than the most optimized chassis-to-chassis phase stability.

7. Wrap Up

With the rapid advancements being achieved by quantum computing systems developers, the electronic test equipment manufacturers who support this industry sector are being tasked to get more creative in order to improve the performance of their product offerings.

Holzworth performance testing confirms that the channel-to-channel stability (phase coherency) is most optimal when all signal sources (channels) are contained within the same chassis. As summarized in Figure 10, Holzworth's industry-first narrowband, high density signal source designs incorporate the latest technologies and techniques to fully optimize both absolute phase stability as well as the critically required phase coherent relationship between the integrated channels.

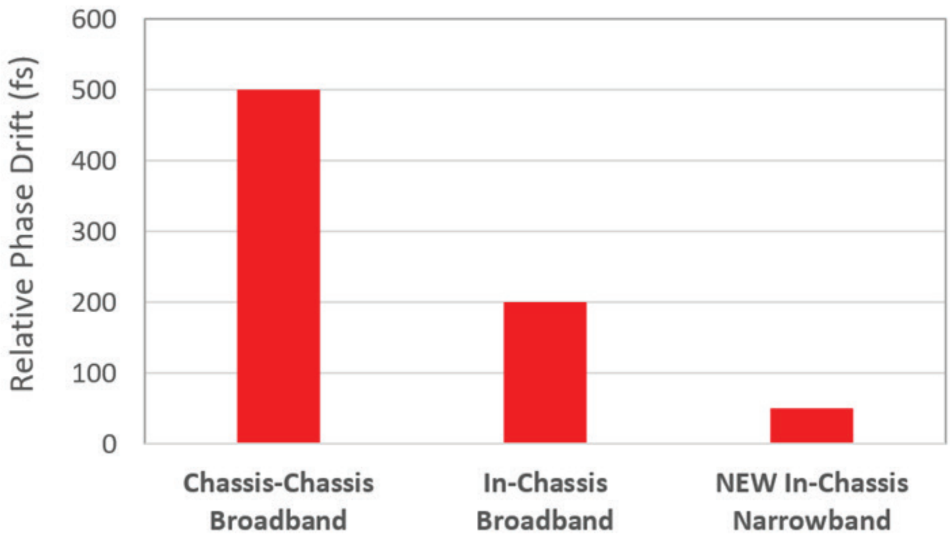

Figure 10: Relative Hourly Phase Drift of Holzworth Signal Sources

Holzworth has a long history of focused efforts to provide optimal channel-to-channel phase coherency with multi-channel RF signal sources. This has made for a straightforward approach to supporting the growing needs of quantum computing systems development as well as deployment of commercially available systems.

Holzworth

Holzworth Instrumentation is a leader in high-performance phase noise analyzers and signal generators for test and measurement solutions in government, commercial, and academic environments. Optimized for ultra-low phase noise performance, Holzworth products offer fast switching speeds, spectral purity, accuracy, and high reliability while meeting stringent performance specifications in a unique form factor. The Holzworth product portfolio includes real-time phase noise analyzers, broadband RF and microwave synthesizers, frequency dividers, amplifiers, downconverters, phase detectors, and phase shifters.

Wireless Telecom Group comprised of Boonton Electronics, CommAgility, Microlab and Noisecom, is a global designer and manufacturer of advanced RF and microwave components, modules, systems and instruments. Serving the wireless, telecommunication, satellite, military, aerospace, semiconductor and medical industries, Wireless Telecom Group products enable innovation across a wide range of traditional and emerging wireless technologies. With a unique set of high-performance products including peak power meters, signal analyzers, signal processing modules, LTE PHY and stack software, power splitters and combiners, GPS repeaters, public safety monitors, noise sources, and programmable noise generators, Wireless Telecom Group enables the development, testing, and deployment of wireless technologies around the globe.

Boonton

Boonton Electronics is a leader in high performance RF and microwave test equipment for radar, avionics, electronic warfare, satellite and wireless communications, and EMI/EMC applications. Used across the semiconductor, military, aerospace, medical and communications industries for more than 70 years, Boonton products enable a wide range of RF power measurements and signal analysis for RF product design, production, maintenance and system integration. The Boonton product portfolio is designed and manufactured in the USA and includes peak and average RF power meters, Real-Time USB Power sensors, RF voltmeters, modulation analyzers, and audio analyzers.

CommAgility

CommAgility is a developer of embedded signal processing and RF modules, and LTE PHY/stack software, for 4G and 5G mobile network and related applications. Combining the latest DSP, FPGA and RF technologies with advanced, industry-leading software, CommAgility provides compact, powerful, and reliable products for integration into high performance test equipment, specialized radio and intelligence systems, and R&D demonstrators. CommAgility engineers work closely with customers to provide hardware and software solutions for the most demanding real-time signal processing, test and control challenges in wireless baseband, semiconductor processing, medical imaging, radar and sonar applications.

Noisecom

Noisecom is a leader of RF and microwave noise sources for signal jamming and impairment, reference level comparison and calibration,receiver robustness testing, and jitter injection. Electronic noise generation devices from Noisecom come in a variety of product types including, noise diodes, built-in-test modules (BITE), calibrated noise sources, jitter sources, cryogenic noise standards and programmable instruments. Calibrated noise sources are available from audio to millimeter wavelengths in coaxial or waveguide modules. Programmable instruments are highly configurable and able to generate precise Carrier-to-Noise, Signal-to-Noise and broad band white noise. Noisecom products arecustomizable to meet the unique needs of challenging applications and can be designed for high power, high crest factor, specific filter responses with a wide selection of input and output options.

Microlab

Microlab is a leader in low PIM (passive intermod) RF and microwave products enabling signal distribution and deployment of in-building DAS (distributed antenna systems), wireless base stations and small cell networks. High performance passive components such as power combiners, directional couplers, attenuators, terminators and filters are developed for broadband applications to support public safety networks, GPS reference signaling, television transmitters and aircraft landing systems. Active solutions from Microlab include GPS signal repeaters for cellular timing synchronization and passive safety monitors for real-time in-building DAS system diagnostics.

Wireless Telecom Group

25 Eastmans Road, Parsippany, NJ 07054 | +1 973 386 9696
Wireless Telecom Group | WTGinnovation | WTGinnovation
www.holzworth.com | H/SG/1121/EN