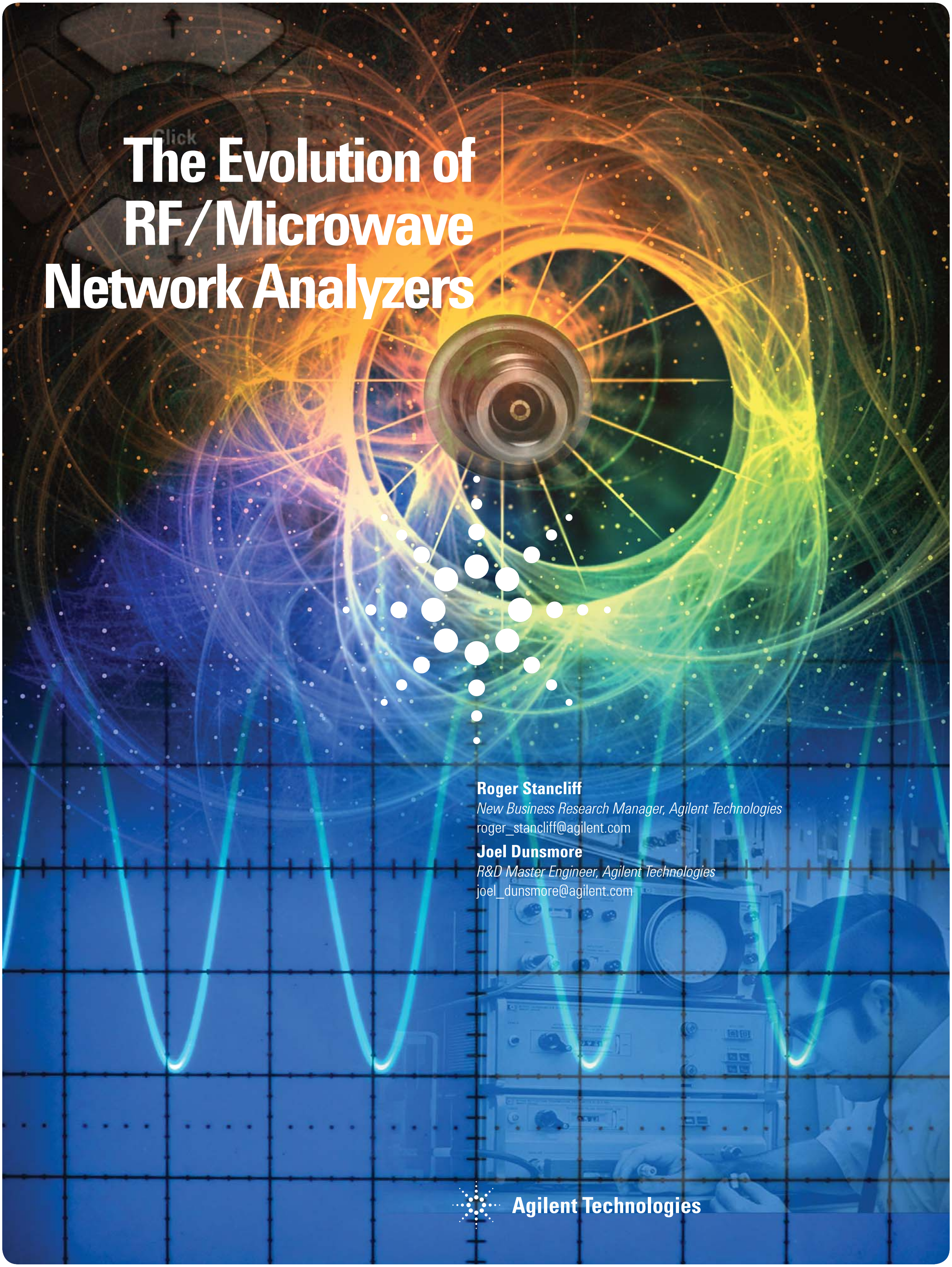

The Evolution of RF/Microwave Network Analyzers

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Precision measurement leads to improved components and systems

The RF/microwave network analyzer has enabled the evolution of high frequency components and how they are designed. The basic ability to measure transmission, reflection, and impedance properties of circuits and devices enables engineers to optimize the performance of amplifiers, frequency converters, signal separation and filtering devices, and other components. The performance of communications and defense systems depends heavily on the capabilities of these components and their test systems.

Looking to the past

In the 1940s and 1950s most high frequency communication systems used tubes (klystron, magnetron) and AM or FM modulation techniques. Rudimentary signal generators, power detectors, and impedance bridges were used to measure the transmission, reflection, and impedance characteristics of these elements to enable successful systems to be built. To construct a modern day Smith Chart, hours of tedious, hand-tuned measurements were taken one frequency at a time. The network analyzer of the day was a swept scalar analyzer combined with tedious, point by point reconstruction of the relative phase characteristics of devices.

By the 1960s, semiconductor technology was just taking hold. Samplers based on semiconductor diodes became the fundamental building blocks of instrumentation. These were used to sample waveforms and enable relative amplitude and phase measurements to be made on signals. Agile signal sources based on backward wave oscillators allowed measurements to be taken across a wide frequency range. The first network analyzer capable of swept amplitude and phase measurements was the 8407* RF network analyzer based on the 8405 vector voltmeter. It allowed comparison of the amplitude and phase of two waveforms but it operated only up to 110 MHz. This was the year that Agilent Technologies, Inc. was spun out of Hewlett-Packard as an independent company.

Figure 1. 8410 network analyzer

In 1967 Hewlett-Packard, predecessor to Agilent Technologies, introduced the 8410 network analyzer which extended swept capability to 12 GHz. This was a bench-top system based on multiple boxes which were integrated to perform the network analysis function (Figure 1). At the same time, the concept of S-parameters was just becoming popular. This put transmission, reflection, and impedance into a single two-dimensional representation which could be rapidly measured and visualized. This was a revolution in high frequency design and enabled engineers to begin designing with the new high frequency semiconductors which were just becoming available. These devices had marginal gain and would not have been very useful without a design and measurement approach that allowed designers to extract all of what was available in these new devices. The interplay and bootstrapping of good measurements, to get the best performance from the devices, helped them both move forward.

*All products mentioned in this article prior to 2000 were sold under the Hewlett-Packard name. This was the year that Agilent Technologies, Inc. was spun out of Hewlett-Packard as an independent company.

By 1970, computers were emerging that could expand instrument capabilities (Figure 2). The 8542 automatic network analyzer was created. This large, three-rack system brought error correction mathematics, pulsed measurements, and other capabilities to circuit designers. The system, though, was three racks of equipment. Modern network analyzers realize all of this capability in a single bench-top box.

Figure 2. 8542 automatic network analyzer system

In 1976 the first integrated, microprocessor controlled network analyzer was introduced: the 8505. This included the synthesized source, receivers, test set, and display in a bench-top box, and it operated up to 1.3 GHz.

In the mid 1980s, the marriage of broadband solid state sources, improved samplers, and microprocessors led to three very important products: the 8510, 8753, and 8720 vector network analyzers (VNA). The 8510 (Figure 3) became the metrology standard for microwave measurements and enabled many improvements in component design. The 8753 (Figure 4) came to market just as manufacturing demands for first generation cell phones were growing. The 8753A was the first fully error-corrected RF network analyzer, and because of its low cost and high capability, it quickly became the industry standard. It was used extensively in wireless component manufacturing, just as the 8510 and 8720 became mainstays for avionics and radar component development and manufacturing.

Figure 3. 8510 network analyzer

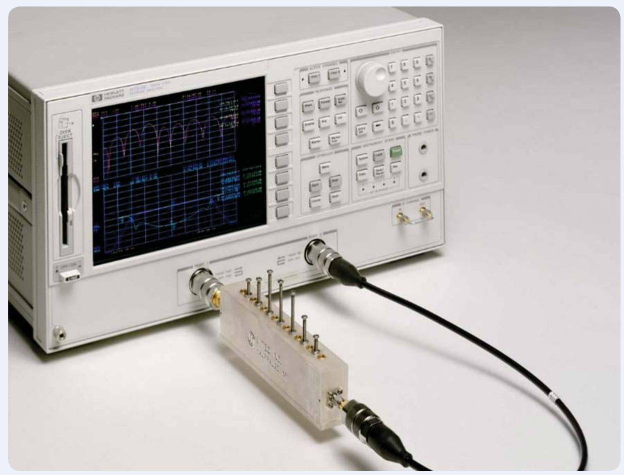

Figure 4. 8753 network analyzer

Emerging at this same time were the first commercial CAE tools for high frequency designers. The interplay between simulation and measurement allowed for acceleration of design cycles and technological capabilities. The first commercial microwave ICs emerged at this time, greatly helped by this measurement and simulation capability. The 8720 was the first fully integrated (one box) microwave VNA and it embodied most of the 8542 ANA's capability in this form factor, 20 years after the 8542 was introduced.

The 1990s saw a huge boom in wireless device deployment. This was the first high frequency consumer market with the commensurate cost pressures and manufacturing volumes. The network analyzer, once an R&D tool, became a mainstream manufacturing device. Speed of measurement became very important. During this time the 84000 RF IC tester was introduced (Figure 5). This was a multifunction, very fast, network analyzer. In some ways, just as in the case of the 8542 automatic network analyzer of 1970, this multiple box IC test system introduced new capabilities which are just beginning their migration into the bench-top network analyzers of today and the future.

Figure 5. 84000 RFIC test system

Current technology

Since 2000, the integration level of RF and microwave devices has expanded rapidly; this new level of integration places new demands on test equipment. This has resulted in the evolution of the network analyzer from a 2-port, swept frequency, measurement instrument into one with much broader capabilities. As early as the late 1990s commercial RF components started using balanced (differential) topology to take advantage of lower power requirements and higher isolation. A key improvement for testing these devices came in 2001 with the introduction of the 4-port ENA (E5071A), the first 4-port network analyzer designed for the mass production market. The latest version (E5071C) is shown in Figure 6.

Figure 6. Agilent E5071C ENA network analyzer

This provided a simulated balun and mixed-mode S-parameters, bringing balanced measurements fully into the RF world. By 2006 the test requirements for balanced measurements extended far into the microwave region, with solutions in the PNA family providing this capability up to 67 GHz. Undoubtedly, these test techniques will need to be extended to even higher frequencies.

A new level of integration in wireless design may combine many of these components, balanced and single-ended, into package-scale integration with a large number of input/output (I/O) ports. While the overall response of this component must meet the same criteria as a design comprised of discrete components, the performance of individual elements in an IC, particularly with respect to isolation, may be degraded. As such, it is very important that the I/O ports be properly terminated, and that mismatch effects at every port be accounted for. We could combine 2- or even 4-port corrected measurements, but this requires properly terminating every other port. The number of measurements grows as N-squared, so with higher port counts this quickly becomes impractical.

Recently, a new generation of test sets have been introduced, which extends the port count of a network analyzer. These N-port systems (Figure 7) use internal switches and couplers to seamlessly integrate the test set with the analyzer giving the N-port test set performance that is directly comparable to that of 2- or 4-port systems. At this time, 8- and 12-port versions of N-port network analyzers are shipping, with 16- and 32-port systems on the horizon.

Figure 7. PNA multi-port system

Calibrating this instrument is time-consuming if done conventionally. However, techniques have been developed to greatly shorten the calibration process, including using electronic calibration modules (Ecal), without compromising measurement quality, providing a full NxN matrix of calibrated measurements with only N-connection steps. Traditional mechanical calibration requires more than N-squared steps.

In addition to the traditional S-parameter measurements, many integrated components include internal amplifiers which require characterization of noise and distortion properties. Current measurement solutions provide for a single connection of multiple-test equipment, but further integration of these advanced capabilities into a single platform is inevitable. The 84000 tester of the 1990s had many of these capabilities and, like the evolution of the network analyzer from the 8542 to the 8720, we see the emergence of new bench-top instruments which embody most of the 84000 capabilities. The challenge to this component-analyzer is to provide a sufficiently good measurement across a wide range of requirements: A network analyzer requires a very fast sweeping source, but this fundamentally conflicts with creating a source with good phase noise and low distortion required for intermodulation measurements.

The wide dynamic range of a network analyzer receiver, which is achieved through the use of narrow receiver bandwidths, is in conflict with the wide bandwidth required for noise measurements. All this gets further complicated since many of the mobile-communications systems are time-domain-duplexed, creating pulsed measurement requirements. And these devices may include frequency conversion, as well as balanced inputs or outputs. All of these challenges must be met without giving up the crucial requirement of fast measurement throughput.

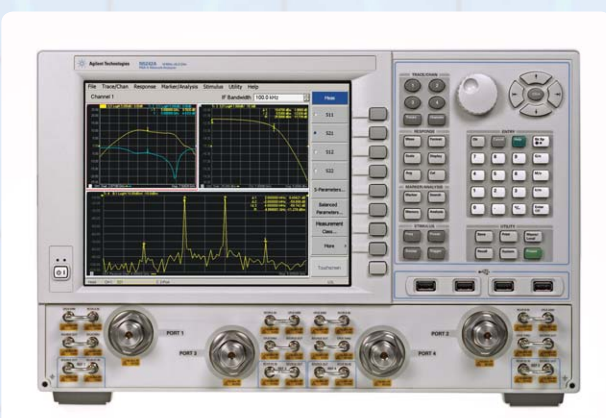

Figure 8. PNA-X component analyzer

Finally, each of these measurements must be calibrated to ensure consistent, repeatable and traceable results. The foundation to solving these challenges is being met by Agilent's new PNA-X network analyzer. The PNA-X (Figure 8) is leading a transformation in enhancing the functionality of a network analyzer to include measurements beyond traditional S-parameters.

Looking to the future

The synergy of combining a traditional network analyzer with more complex stimulus-response test systems provides improvement in the overall accuracy and correction of results, because the network analyzer function allows characterizing the mismatch and interaction between the test equipment and the device-under-test. At the same time, the types of stimulus are evolving to include complex modulation, noise, and even DC parametric drive. The responses measured are becoming much more complex, requiring sophisticated post processing of data. Thus, the integration of multifunction components into a single DUT will drive the integration of multi-function test into a single, coherent test system.

New applications, such as the frequency converter application in the PNA, which provided the first fully corrected vector mixer calibration will continue to improve, extending to such areas as measurement of converters with an embedded local oscillator, and digital RF, where components have a digital interface for one port and an RF interface for the other. Components such as these will require marrying the capabilities of today's logic and protocol analyzers with RF signal sources and spectrum analyzers.

Just as the communications networks are becoming more distributed, there is a drive to distribute testing throughout these systems. Portable and hand-held instrumentation will be required to service and support these systems; these small instruments will need a level of capability previously found only in multi-box systems. The capability of these multi-box systems will need to be distributed across these far-flung networks, perhaps even becoming embedded in them. Technologies such as IEEE standard 1588 precision time protocol will allow synchronization of data and triggering across these networks.

One might be tempted to conclude that the need for parametric test could disappear. Why not do a functional test on every component? In fact, while functional test will provide a convenient pass/fail test that could be used at the end of a production process, the functions that must be verified may become so complex that true functional test is not practical to ensure that every unit will work in all environments. For example, the input filter of a radio system is designed to remove interfering signals. A functional test to verify the correct operation of the system in the presence of other signals might mean creating every possible scenario of interfering signal, and testing the bit error rate (BER). A more efficient way of verifying this system might be to apply a swept sine to the input of the system and determine the cut-off characteristics of the filter. But, as the interfaces between components become more difficult to access, new ways of validating designs and controlling manufacturing processes will be required.

Today, it is possible to embed an Agilent logic analyzer into an FPGA design. In the future, complex stimulus/response capability, or even an entire network analyzer may be designed directly into RF circuits, providing the ultimate realization of design for test. As interfaces between components become more complex, and more difficult to probe, it seems that integrated component test may be the only logical solution to verify future generations of RF and microwave systems.

Conclusion

We have postulated that components and network analyzers helped bootstrap each other to accelerate technological progress. Going forward, this bootstrapping is increasingly happening between simulation and embedded test inside the chips themselves. The network analyzer will be used to determine the fundamental characteristics of the chip's building blocks to feed simulation engines and to verify the chip and embedded test instrument designs.

Large opportunities for stimulus/response characterization — the forte of network analyzers — also exist outside of the electronic device world in measuring attributes of materials, even down to the nanometer scale. The growth of these new applications and measurements will keep the network analyzer an essential tool for many years to come.

A Very Brief History of Network Analyzer Calibration

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Network analyzers — being vector measuring instruments — have the unique ability to apply error correction techniques to improve their accuracy. Initially, short circuits were used to establish the maximum level of reflection magnitude. Precision transmission lines, sliding loads, and sliding shorts were used as impedance standards. Precision attenuators, such as piston and rotary vane variable attenuators, were used to establish transmission loss reference levels. Grease pencils were used to mark the reference level on a CRT display or meter display. Such calibration methods were able to remove some of the measurement scalar errors. The 8407 and 8410 swept frequency vector network analyzers made it possible to correct some of the vector errors. The 8542 made full vector error correction possible for the first time. It also allowed imperfect standards, such as the open-standard, to be defined by a device model. The short-open-load-through calibration method was fully enabled.

A surge in research on VNA calibration methods brought us the through-reflect-line family of calibrations, which was implemented in the 8510. Measurement accuracy became limited by the accuracy of the calibration standards. Thus, ultra-precision reference transmission lines and slotless female contacts were introduced. Electronic calibration was invented to simplify calibration; a single connection and a software controlled sequence completed the process. Multi-port, differential, and non-linear calibration methods and standards are the current challenges.

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