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Product Testing Where RF Meets Broadband – Convergence of RF, Optical, and Digital Test Environments

Erik Roberts
Keithley Instruments, Inc.

Jeff Slaughter
Keithley Instruments, Inc.

Mike Esmond
Mindspeed Technologies

Broadband Test Environment

The communications industry is buzzing with the promise that broadband technology and services will enable a truly universal method of information exchange and a fabulous array of new consumer products. The merging of key technologies into one common transmission media now allows broadband communications that simultaneously modulate and transmit voice, data, and multimedia video over one carrier type, such as wireless links, cable, or optical fiber.

The compression of dense modulated information is widening the bandwidths of all these carriers. For mobile wireless links, 3G technologies essentially triple the carrier channel bandwidth of current US CDMA systems to 3.69MHz (US standard CDMA200), or to 3.84MHz for the European Wideband CDMA (W-CDMA). Cable modem subscribers can experience IP bandwidths from 500Kbps to 1.5Mbps, depending on network traffic and congestion. Optical fiber technology already transmits digital data at 2.5Gbps, with 10Gbps systems currently rolling out, and 40Gbps hardware in field trials.

While the defined standards, modulation, hardware, and (in some cases) services for these systems are dissimilar, they actually begin to converge in terms of RF design and testing. High speed digital bit rates near and beyond

Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, Ohio 44139
(440) 248-0400
Fax: (440) 248-6168
www.keithley.com

hundreds of megabits per second clearly fall into the RF regime because of their high frequency spectral components. Therefore, RF design and test engineers must now expand their thinking beyond traditional approaches, and consider the impact of related technologies on engineering methods and decisions. Where continuous DC testing was adequate in the past, broadband considerations call for additional RF test equipment and analysis methods. In many firms, both product development and production testing must be revamped to accommodate the convergence of optics, high speed digital, and RF technologies, especially for Synchronous Optical Networks (SONET).

SONET Device Switching

The primary driving force behind broadband communications is the possibility of anytime, anywhere Internet access at speeds greater than 1Mbps, along with the ability to handle data, voice, and video seamlessly. Wireless access methods such as Local Multipoint Distribution Service (LMDS), cable/wireline methods such as Digital Subscriber Line (DSL), and fiberoptic methods such as SONET all seek to achieve this, albeit with different arrays of hardware and access protocols. SONET often prevails for a number of reasons.

For example, the backhaul[1] of current broadband networks is usually achieved through fiberoptic transport. Regardless of "last mile" access technology, the high bandwidth and data rates available with optical transport makes it the most attractive long-haul (>40km) technique. Thus, competing technologies like DSL or LMDS often use optical fiber to connect nodes on their network and to reach remote locations, often as part of a transcontinental link. This is due to the service-independent nature of the fiber networks, specifically of SONET technology.

With the growing prevalence of SONET networks, many RF test system designers are now involved with SONET device testing. Such tests revolve around the SONET standards defined by the American National Standards Institute (ANSI) and similar ones defined by the International Telecommunications Union (ITU) in its Synchronous Digital Hierarchy (SDH). In addition to synchronous networking, these standards allow compatibility between vendor equipment and transport of numerous services, such as ISDN. SONET and SDH standards define optical carrier (OC) and synchronous transport module (STM) hierarchical levels, respectively, that define data bit rates and pulse widths for network transmission (***Table 1***).

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[1] The practice of routing telecommunications traffic beyond its intended destination, and then back to the intended destination, usually for the purpose of taking advantage of tariffs or prices that are lower than those afforded by direct routing or to achieve other desirable network features.

Table 1. SONET and SDH Transmission Hierarchy.

SONET Hierarchical Level	SDH Hierarchical Level	Data Rate	Pulse Width
OC-1	—	51.84Mbps	19.3 ns
OC-3	STM –1	155.52Mbps	6.45 ns
OC-12	STM-4	622.08Mbps	1.6 ns
OC-24	STM-8	1244.16Mbps	80 ns
OC-48	STM-16	2488.32Mbps (2.5Gbps)	400 ps
OC-192	STM-64	9953.28Mbps (10Gbps)	100 ps
OC-768	STM-256	39813.12Mbps (40Gbps)	25 ps

As SONET devices become more integrated and multiple high speed channels exist in a single package, the challenges of developing a cost-effective and complete test solution increase. The high cost associated with today's high speed digital communications test equipment prevents multiple sources and analyzers within the test setup. Likewise, time and resources prevent the manual effort involved in connecting and disconnecting cables in order to test all channels within a device. In a typical crosspoint switch today, there may be anywhere from 36 to 136 or more input and output channels; similarly, many other building blocks, such as clock data recovery (CDR) units, are being integrated into arrays of 16 or more.

This high level of integration requires a new means of testing in order to keep test costs down. One such way is the use of RF switch matrices within the test setup, which allows for an integrated, high throughput approach to testing multiple channels with minimal test equipment resources. For example, an NNXNN digital cross-connect switch (DCS) would require a 1XNN microwave switch matrix to route an input signal source to all channels of the DUT. Another 1XNN matrix could route the outputs of the DUT to a communications analyzer for eye diagram measurements as well as Bit Error Rate (BER) tests. This approach allows for maximum use of the test instruments and full coverage of the DUT with no need for manual hooking and unhooking of cables (***Figure 1***).

Combined with software calls over a GPIB interface, a quick and complete Automatic Test program (ATP) can be developed to verify and measure all possible paths, which would otherwise be impossible to do in a reasonable timeframe by manual methods. This method of using microwave switches could also be applied to multiple test resources needing access to the same I/O of the DUT without disconnecting the test setup. The use of RF switch matrices in the test equipment allows for an integrated, high throughput approach to testing many devices. In addition to switching, it may also be necessary to condition the high frequency signals with amplifiers, attenuators, RF couplers, dividers, or other components, depending on the critical test specifications and the parameters to be extracted from the output.

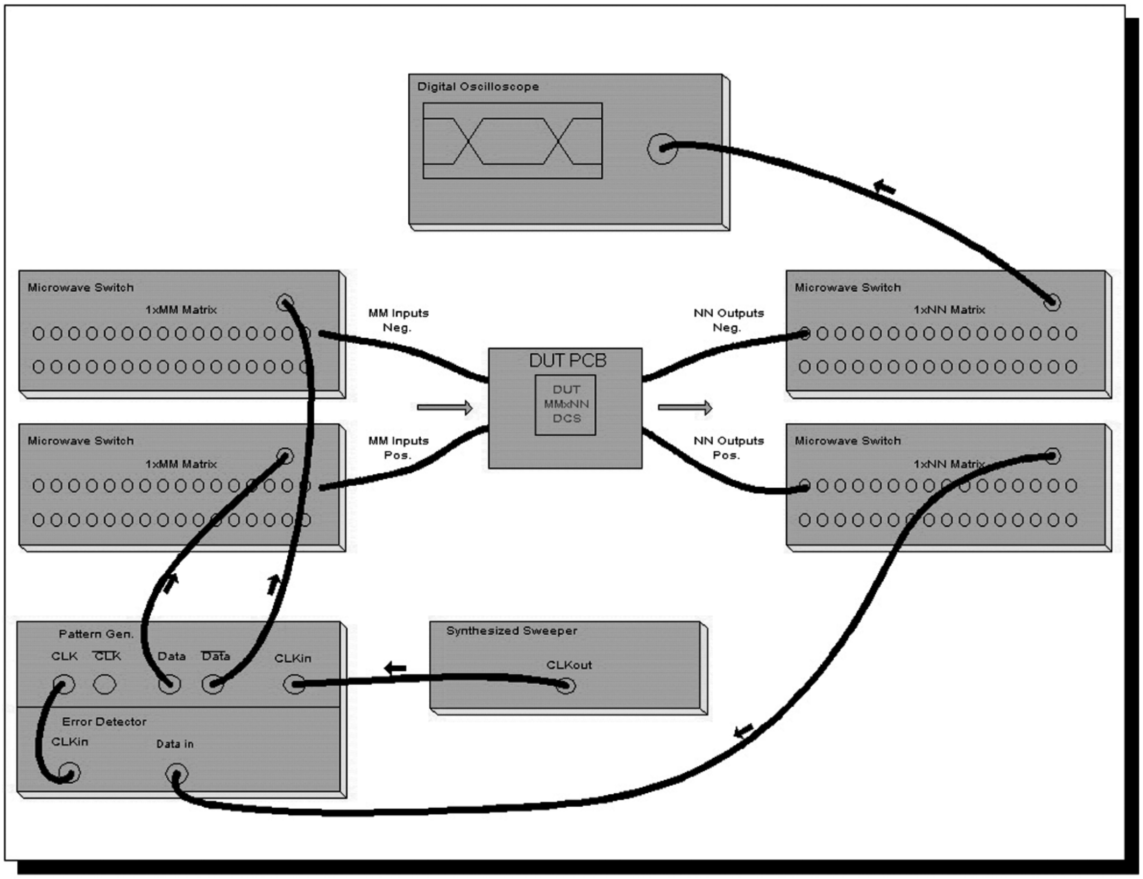

Figure 1. Typical configuration for testing BER of SONET cross-connect switches. The microwave switch allows upwards integration of test hardware and user devices.

Switch and Other Test Hardware Needs

The key to successful signal routing is adequate bandwidth. The switch or routing solution chosen should have as a minimum the bandwidth of the DUT, and preferably equal to the bandwidth of any higher frequency source and measurement equipment. Even so, higher bandwidth may be desirable to ensure that the system is not band-limiting for any test scenario that is apt to arise. ***Table 2*** lists some key attributes of a microwave switching system. ***Figures 2*** and ***3*** show typical microwave switch system performance.

In addition to proper frequency selection, insertion losses and VSWR are critical to SONET testing. Losses greater than one or two dB attenuate peak signal levels, and increase rising and falling edge times. Poor VSWR indicates internal reflections due to impedance mismatches, and can lead to inter-symbol interference (ISI) due to the stray signals caused by these reflections.

Therefore, good connector matching and proper termination is a key test requirement. These parameters should be extracted from a vector network analyzer (VNA). A good method

Table 2. Typical switching system features and specifications for SONET device testing.

PERFORMANCE SPECIFICATIONS		
Impedance (ohms)?	☐ 50Ω ☐ 75Ω ☐ Terminated ☐Unterminated	
Connector Type?	☐ N-Type ☐ SMA ☐ 3.5 mm ☐ K (2.9mm) ☐ Other	
Frequency Range?	_________ ☐ MHz ☐ GHz	
Insertion Loss:	_________ dB @ _________	(frequency: ☐ MHz ☐ GHz)
Crosstalk / Isolation:	_________ dB @ _________	(frequency: ☐ MHz ☐ GHz)
Return Loss: or VSWR	_________ dB @ _________ _________ @ _________	(frequency: ☐ MHz ☐ GHz) (frequency: ☐ MHz ☐ GHz)
Peak Input Signal Level	_________ ☐ dBm ☐ milliwatts	
Phase Matching	_________ º @ _________	(frequency: ☐ MHz ☐ GHz)

of qualifying system bandwidth performance is to collect VNA data beyond the known frequency of operation. Even though the extended bandwidth may be outside the specified operating region of the system or test components, this will provide a clearer picture of what may be occurring at the harmonic resonant frequencies.

The number of connectors and through-paths in the test system can also contribute to adverse signal effects due to mismatches and insertion losses. Therefore, minimizing the number of components such as connector adapters in the through-paths has a beneficial effect on test accuracy. For the same reason, it is also recommended to keep through-paths as short as possible.

Long runs contribute to rising-edge and phase delay because of the added resistivity and capacitance associated with cables. Edge delay affects rise time and the eye pattern mask, giving rise to errors such as phase delay, which is a measure of transit time through a device at a particular frequency. Phase delay distortions produce over- and undershoot and ringing of pulses, contributing to jitter and ISI. In differential signal systems, or systems where phase-matching is critical, equal-length, phase-matched paths are recommended. Be aware of the desired frequency where phase-matching is critical, and stipulate this requirement for the routing solution.

Digital Pulse Bandwidth Requirements

High speed digital signals exhibit RF behavior in real-world devices, which creates a need for RF or microwave components when routing these signals in test systems. Although optical and digital engineers may not be accustomed to thinking of RF approaches in design and testing, they must now be aware of RF metrics in these activities. Equally, RF design and

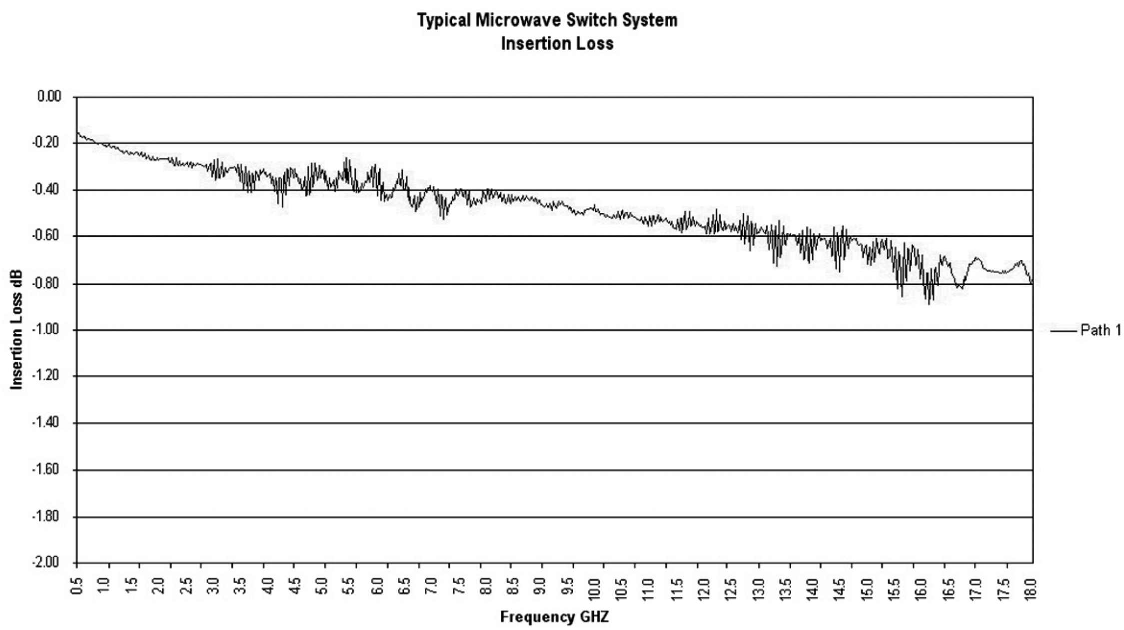

Figure 2. Typical Insertion Loss Graph of a microwave switch system. Path 1 consists of a SPDT and SP6T electromechanical switch and interconnection cable.

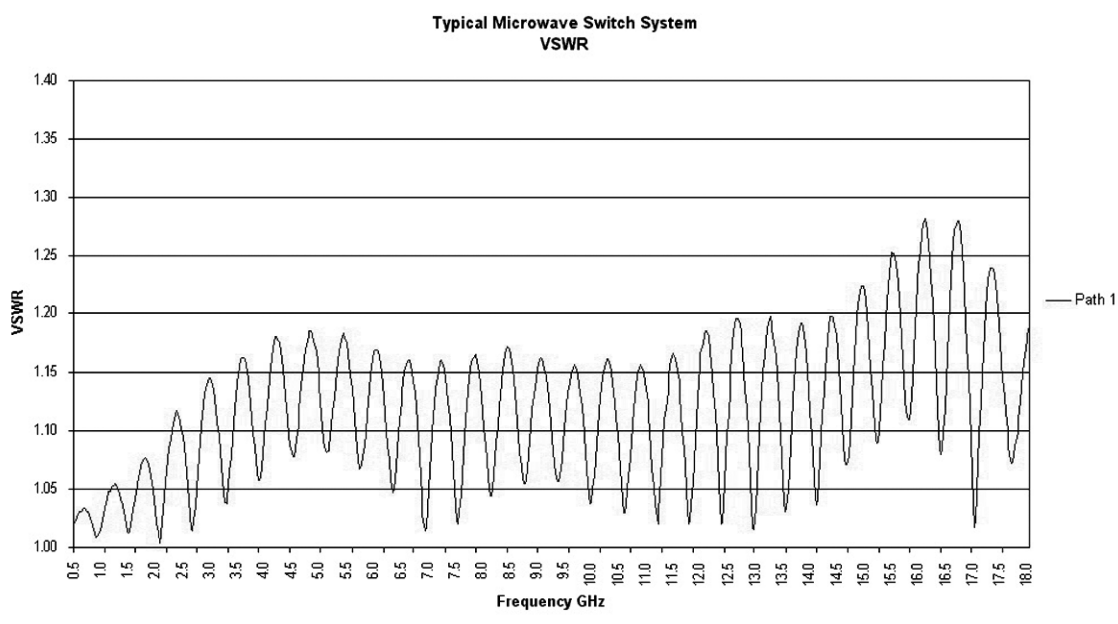

Figure 3. Typical VSWR Graph of a microwave switch system. Path 1 consists of a SPDT and SP6T electromechanical switch and interconnection cable.

test engineers must be familiar with the testing of modulated high speed digital and optical signals.

Maintaining modulation integrity during RF to optical transformation processes (and vice versa) is critical to ensure that no errors are present in the bit stream, which would cause data loss. Similarly, hardware and measurement equipment, such as switching matrices, must have a wide enough bandwidth to resolve the original signal. Resolving bit patterns and data rates up to 40Gbps (OC-768) without causing errors is critical to the proper test and analysis of high speed components and systems.

While fundamental pulse frequencies may be adequately supported by the current test equipment, unless the higher harmonics are being passed through the system, the complete waveform may be not be visible. (See Appendix A.) A good approximation technique to determine the amount of bandwidth needed to resolve an adequate signal is to take the Fourier transform of the digital pulsed signal, which can be approximated as a periodic square wave for purposes of the analysis. The Fourier coefficient of a periodic pulse is given by:

$$F_n = \frac{Ad}{T} \frac{\sin\left(\frac{n\omega_o d}{2}\right)}{\frac{n\omega_o d}{2}}$$

where A is the pulse amplitude, d is the duration of the pulse, T is the period of the pulse and ω_o is the fundamental frequency in radians.

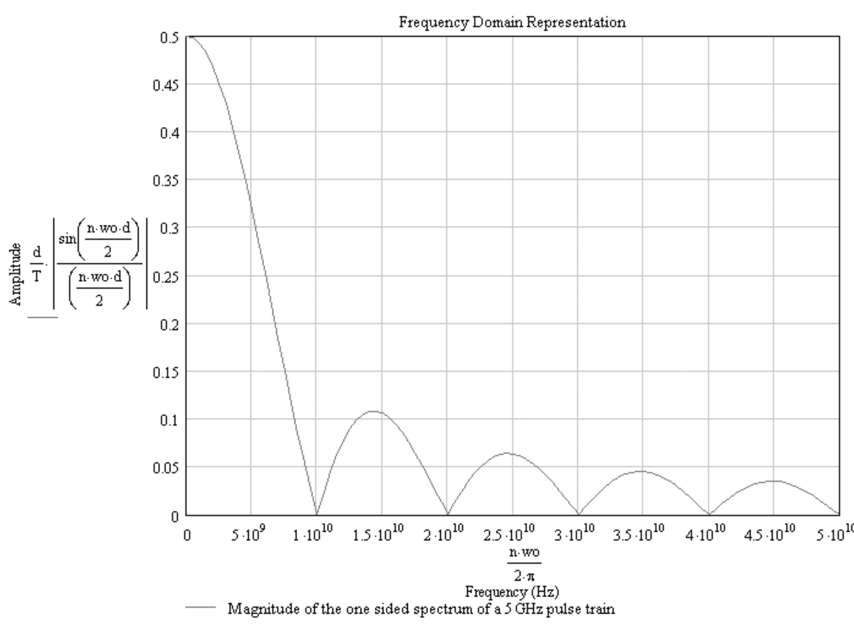

Figure 4. ***The magnitude of the one-sided spectrum (positive n only) of a periodic pulse.***

Figure 4 illustrates which frequency components are dominant contributors to a periodic pulse with ω_o equal to 5GHz/2π (similar to OC-192 with data rates at 9.95328 Gbps) and duration (d) at T/2. The test setup bandwidth would need to be at least 15GHz in order to pass only the fundamental and third harmonic. Even higher bandwidths are necessary if inclusion of the third order harmonic is not sufficient to resolve the signal adequately for the tests; in other words, the fifth harmonic and beyond may be needed.

Such requirements are emphasized by the eye diagrams of high speed digital signals. An eye diagram as seen on the output of an oscilloscope is a signal that has every one and zero in a bit-stream superimposed. It is a convenient way to examine parameters such as rise time, overshoot, jitter, and bit errors. The eye diagram property most important in analyzing these parameters is defined by the eye mask, also called the decision region (***Figure 5***). As applied to a receiver, this is the region that determines if a '0' or '1' has been received. An incorrect determination means a bit error has occurred. The horizontal parameter of interest is called the eye width, which is approximately 324ps for this waveform. The vertical parameter is measured in terms of eye height, which is approximately 411mV. The eye mask is typically set at the 10–90% or 20–80% risetime margins of the pulse.

Figure 5 is an eye chart for an OC-48 signal. This signal was routed through a coaxial microwave switch. The relative "squareness" of the wave is clearly seen, mimicking the original pulsed waveform. In contrast, ***Figure 6*** is the same signal at OC-192 10Gbps rates showing that the eye diagram has lost some resemblance to the original square wave shape, with fewer harmonic frequencies passing through the system.

The decision region now has narrower limits, making the test more sensitive to jitter since the signals have smaller tolerances to error. The eye width has been reduced to approximately 70ps (attributable to the faster and shortened pulse width), and the eye height has been reduced to approximately 320mV. A correct bit should be interpreted if the zero crossing is in phase with the original data stream (i.e., is equivalent to the pulse width and peak-to-peak points that differentiate 1's and 0's). Therefore, it's necessary to adjust decision regions when going to higher data rates on the same test equipment.

40Gbps and Beyond—The Dilemma and Current Solutions

As field trials are underway for OC-768 systems, state-of-the-art pattern generators and analyzers are yet to reach beyond 40Gbps. Harmonics for 40Gbps signals go beyond 100GHz, whereas current SONET test equipment tops out near 50GHz. It is unlikely that traditional equipment will accommodate these frequencies anytime in the near future. With that in mind, developing test routines that work around this limitation may be required. The

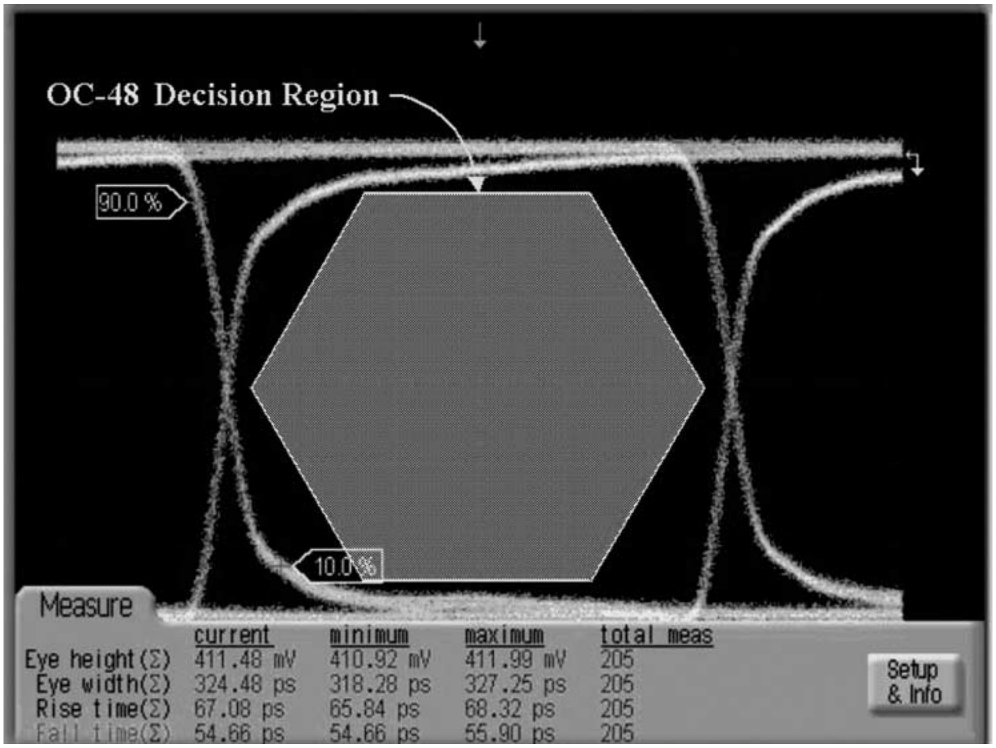

Figure 5. *Eye diagram showing decision region for OC-48 signal going through a DCS device and microwave switch system.*

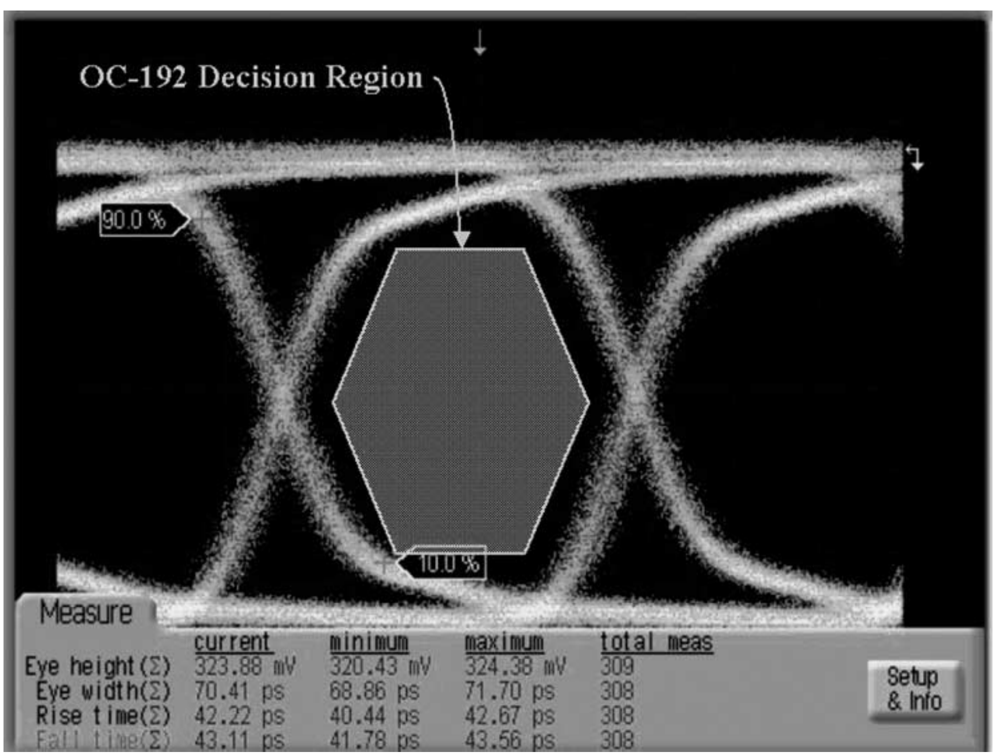

Figure 6. *OC-192 eye diagram showing rounding effects due to bandwidth limitations of test system.*

sensitivity of the signal to the test equipment, and the ability of the equipment to resolve signal parameters, may make it necessary either to relax or change the measurement criteria. It may also be necessary to change the signal routing from coaxial to waveguide, and make other changes in the test environment.

The following measurements checklist summarizes the steps in selecting/specifying a test system or equipment adequate for signal analysis:

1. Know the test requirements and what needs to be accomplished.
2. Select source and measurement equipment and a switching system with adequate specifications and features
3. With the DUT in place, measure/calculate the bandwidth performance of the entire test system from end to end, including:
   a. Insertion losses
   b. Impedance matching
   c. Phase and group delay
4. Select appropriate cables and components to interconnect individual pieces of equipment. Know phase-matching requirements and path lengths and their impact on the desired test.
5. In the test setup, be mindful of the number of channels in the signal routing. The more throws on the individual switches, the poorer the performance, so make the necessary trade-offs between channel density and performance.

Observing these guidelines will make it easier to use current broadband technology to bridge the gap between digital, RF, and optical designs, including test systems. Building a close, flexible working relationship between engineering disciplines will make this easier. RF designers must be knowledgeable about digital signals and pulses, down to the level of Fourier analysis. Understanding the behavior of electro-optical signals is critical to the RF designer who must create state-of-the-art hardware and accurately test it. Digital and optical engineers should understand some basic RF parameters and incorporate this into analysis of their signals. Also, test environments should be evaluated to make certain they adequately support the necessary tests. Depending on the signal of interest, this may push test hardware to the edge of its capabilities and create a need for new test products.

Appendix A

Required Bandwidth is Higher than Fundamental Pulse Rates

Digitally modulated carriers are pulsed signals whose pulse profiles may be represented as a series of square waves. Square waves are periodic signals that maybe represented as sum of sinusoidal signals.

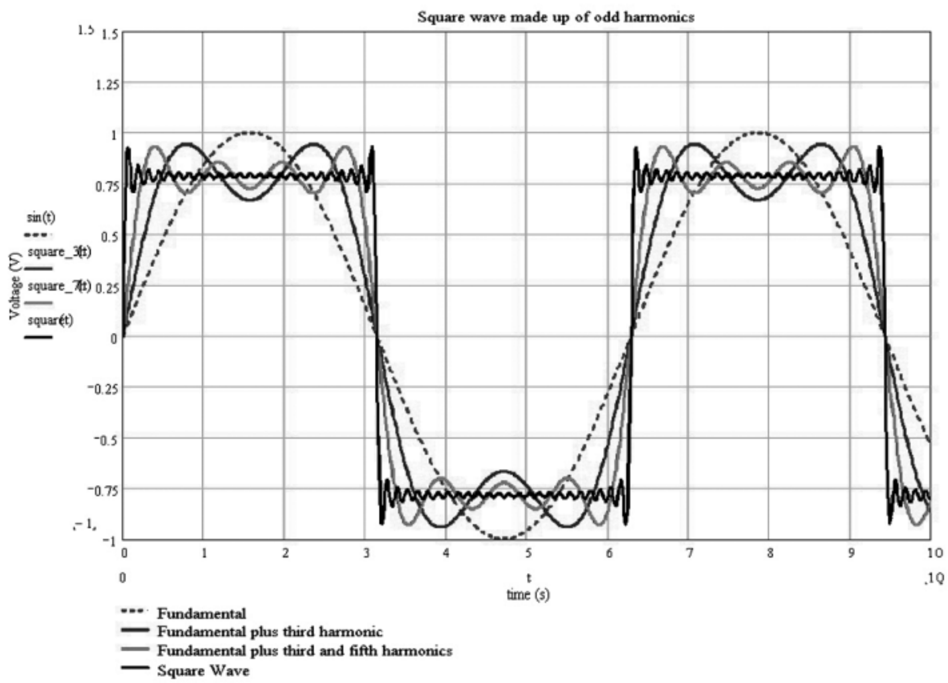

Figure 7. Periodic square wave shown being composed of sine wave harmonics.

The additions of the higher harmonics to the function sharpen the transitions of the fundamental sine wave, eventually resulting in the original square wave. Figure 7 shows that inclusion of higher harmonics enables greater resolution of the original pulsed square wave. This underscores the need for high bandwidth test equipment and related hardware.

Specifications are subject to change without notice.

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Keithley Instruments, Inc. 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
1-888-KEITHLEY (534-8453) • www.keithley.com

Sales Offices:

BELGIUM:	Bergensesteenweg 709 • B-1600 Sint-Pieters-Leeuw • 02-363 00 40 • Fax: 02/363 00 64
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