A New Instrument for Waveform Analysis of Digital Communications Signals

The HP 83480 digital communications analyzer combines an optical reference receiver with an oscilloscope and communications measurement firmware. Its measurements meet the requirements of the SONET and SDH fiber-optic communications standards.

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The telecommunications industry is currently experiencing a period of rapid growth and change. Just a few years ago a digital network needed a capacity of only a few hundred megabits per second to handle all the telephone conversations between such major metropolitan centers as San Francisco and New York. Today, to carry all the voice, fax, video, and data transmissions between these cities, a system needs a capacity of at least 2.5 gigabits per second (Gbits/s). Even this is not enough for the future. Ten-gigabit-per-second systems are already beginning operation in some areas, and researchers are hard at work increasing capacities into the range of 40 to 100 Gbits/s over the next several years.

This growth has spurred several fundamental changes in transmission systems. First is the rapid conversion from copper or microwave transmission media to fiber optic systems. Optical fiber offers many advantages over traditional copper: extremely wide bandwidth, low loss, high immunity to interference, and virtually no crosstalk between channels. Moreover, fiber does not suffer the annoying propagation delay typical of satellite-based communications. (It is easy to tell when a long distance call has been routed via satellite because of the noticeable delay between when you speak and when the listener hears your words.)

A second major change is the increasing importance of worldwide transmission standards. In years past, every equipment manufacturer used a separate proprietary transmission format, so the transmitter in one city and the receiver in another city had to be manufactured by the same vendor. With the deregulation of the U.S. phone system and the ever increasing importance of international communications, such proprietary schemes have become impractical.

SONET and SDH Standards

Two primary fiber-optic standards have emerged: SONET (Synchronous Optical Network), developed first by Bellcore and adopted by the American National Standards Institute (ANSI),[1] and SDH (Synchronous Digital Hierarchy), developed by the International Telecommunications Union (ITU).[2] SONET is primarily a North American standard and SDH is used in most of the rest of the world. An important objective of these standards is to ensure compatibility between equipment manufactured by different vendors. To achieve this the standards address such varied requirements as the physical properties of the optical signal and the transmission protocols and coding formats employed. It is a tribute to the cooperation between ANSI and ITU that in all practical respects, SONET and SDH are virtually identical.

Transmission System Design

A simple fiber-optic transmission system (Fig. 1) consists of a transmitter, a fiber-optic cable, and a receiver. The transmitter usually employs a digitally modulated laser diode operating at a wavelength of either 1300 or 1550 nm. The individual voice and data signals appear as low-rate electrical tributary signals that are time division multiplexed into a serial digital stream applied to the laser input. The laser's output is modulated in a simple nonreturn-to-zero (NRZ) format: it is turned on for the entire duration of a logical one pulse and turned off (or nearly off) for the entire duration of a logical zero pulse.

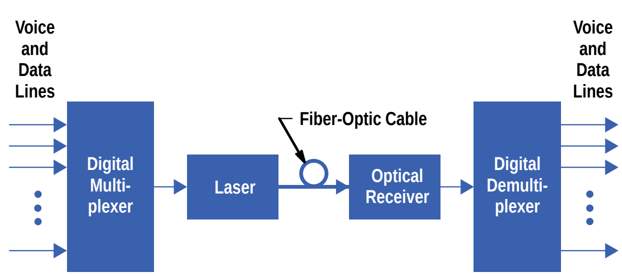

Fig. 1. *Fiber-optic transmission system.*

The fiber-optic cable is typically single-mode fiber with a 9-μm core diameter. The receiver consists of a p-i-n or avalanche photodiode serving as an optical-to-electrical (O/E) converter, with appropriate amplification, timing, and detection circuitry. A demultiplexer at the receiver output extracts the individual tributary signals. Real systems also often employ other network equipment such as digital cross-connects, optical amplifiers, and add-drop multiplexers.

The SONET and SDH standards place strict limits on the performance of each element in the system. At the physical level, transmitter specifications include output power, optical waveform shape, and extinction ratio. For the receiver, such parameters as sensitivity, electrical waveform shape, and output jitter are important. In the past, waveform characteristics of the system have been measured with a high-speed oscilloscope. Electrical signals could be measured directly, but to measure optical waveforms, a photodiode O/E converter was required in front of the oscilloscope.

The SONET and SDH standards impose new requirements on the optical waveform that are not easily measured with a conventional oscilloscope. One requirement, for example, is that the O/E converter be an optical "reference receiver" having a tightly controlled frequency response, specified as a fourth-order Bessel-Thomson filter whose 3-dB frequency is three quarters of the bit rate.[3] The resulting eye diagram (see subarticle "***Eye Diagrams and Sampling Oscilloscopes***") is compared against a specified mask that defines "keep out" regions for the waveform. The mask shape is designed to ensure that the quality of the waveform is sufficient to achieve satisfactory transmission performance. To make this measurement an oscilloscope must include a calibrated optical reference receiver, a way to generate the SONET/SDH mask automatically, and a way to compare the eye diagram accurately to the mask.

The Digital Communications Analyzer

The HP 83480 digital communications analyzer (Fig. 2) is the first commercial product to combine a SONET calibrated reference receiver with an oscilloscope and communications measurement firmware in a single package. It is based on proven HP digital sampling technology first introduced in the HP 54120 sampling oscilloscope in 1987. The HP 83480 is designed to address several limitations of existing technology. These include lack of overall optical calibration, incompletely calibrated SONET/SDH reference receiver path, and lack of flexible firmware measurement algorithms.

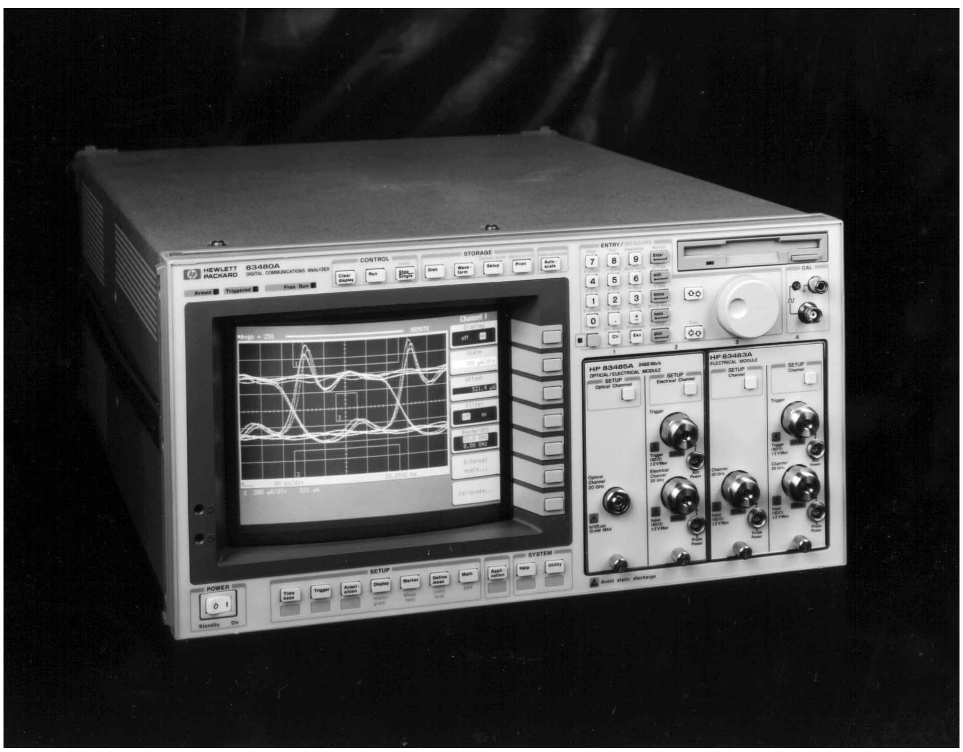

Fig. 2. *The HP 83480 digital communications analyzer combines a SONET calibrated reference receiver with an oscilloscope and communications measurement firmware.*

Overall Optical Calibration. To measure an optical signal before introduction of the HP 83480, a separate O/E converter had to be connected to the oscilloscope's vertical channel input. Rarely was the exact conversion gain of this combination known with any degree of accuracy, so the overall optical channel could not be considered a calibrated path. In the HP 83480, the optical channel is fully calibrated and displays a readout in optical watts. In addition, each optical channel includes a separate average power meter that approaches the accuracy of a dedicated optical power meter.

Calibrated SONET/SDH Reference Receiver Path. Current SONET/SDH standards place strict limits on the frequency response of the optical reference receiver but do not define requirements for the oscilloscope to which it is connected. The HP 83480 design team recognized early in the project that it made little sense to tightly control the reference receiver if the oscilloscope bandwidth and frequency response were insufficient to display the signal accurately. The team decided the answer was to apply the SONET/SDH frequency response tolerance requirement to the entire channel response, not just the O/E converter (see Fig. 3). Although this added to the design challenges and is more stringent than required by the standards, it vastly increases the user's confidence in the measurement.

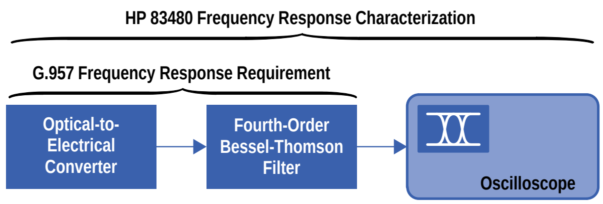

Fig. 3. *The SONET/SDH G.957 standard requires calibration of the optical receiver to a specified accuracy. In the HP 83480 digital communications analyzer, the entire instrument including the oscilloscope is calibrated.*

Flexible Firmware Measurement Algorithms. While other oscilloscopes have incorporated certain mask and parametric measurement capabilities, none has included all the measurements desired by users, and those provided have not always performed satisfactorily over the full range of expected waveforms. The HP 83480 design team placed a high priority on developing a complete set of features that correctly measure a wide range of waveform shapes.

Overall Design

The HP 83480 digital communications analyzer incorporates a modular design consisting of an oscilloscope mainframe together with various vertical channel plug-ins (Fig 4). The mainframe contains the analog-to-digital converter (ADC), time base, CPU, user interface, and display circuitry, while the vertical channel modules contain the O/E converters, samplers, IF amplifiers, and power monitoring circuitry. The various plug-ins cover different bandwidths, wavelengths, sensitivities, and fiber-optic media.

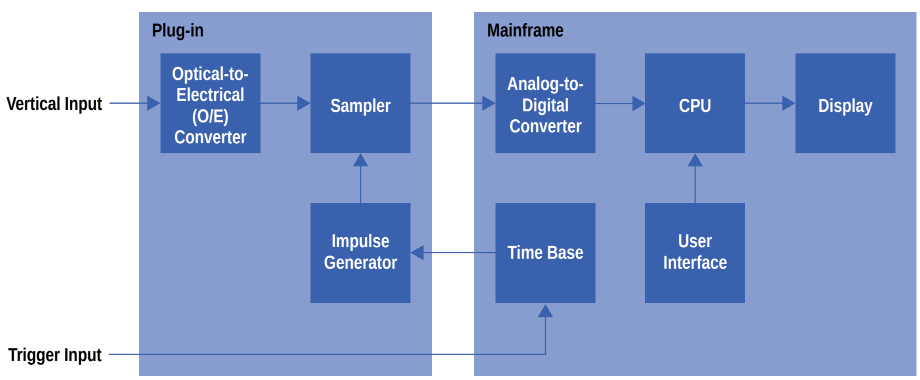

Fig. 4. *HP 83480 system block diagram.*

The mainframe/module approach offers maximum flexibility to the user. During initial market research, customers frequently expressed the desire to preserve their investment by being able to upgrade their oscilloscopes easily in the future.

The mainframe hardware is based on the modular HP 54720 oscilloscope platform introduced in 1992.[4] Major differences in the HP 83480 include the acquisition system, the internal firmware, and the front-panel design. The use of the HP 54720 mainframe provided two major opportunities for leverage of existing designs. First of all, it provided proven modular mainframe components complete with power supply, display, computer, and high-speed graphics. Secondly, it offered a software system that was designed with the ability to substitute different acquisition architectures with a minimum of engineering resources.

Acquisition System

The HP 83480 acquisition system has a repetitive sequential sampling architecture conceptually similar to that of HP's earlier high-speed sampling oscilloscope, the HP 54120. (Unlike the newer HP 54720, the HP 54120 did not use a modular design.) This approach provides the extremely high bandwidth necessary to display lightwave signals to beyond 10-Gbit/s rates. The acquisition system, split between the mainframe and plug-in, consists of a time base and sequential delay generator, a high-frequency trigger, microwave samplers, track-and-hold circuits, and analog-to-digital converters (Fig. 5). The plug-ins for the HP 83480 are specific to this sampling architecture. They cannot be used in the HP 54720, nor can HP 54720 plug-ins be used in the HP 83480.

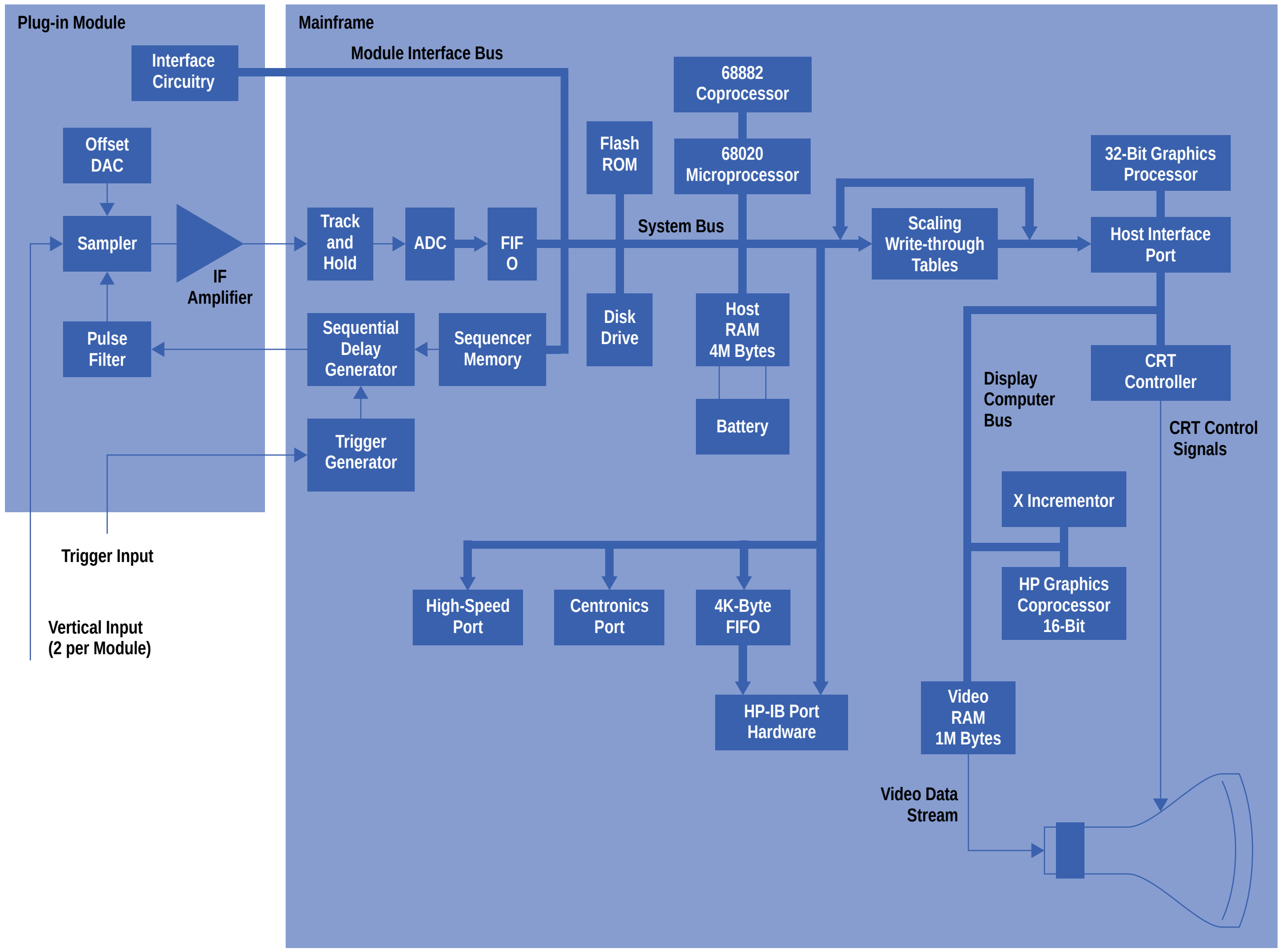

Fig. 5. *HP 83480 hardware block diagram.*

An acquisition cycle is defined as the sequence of events that must occur to acquire a single data point per enabled channel. Normally, many acquisition cycles are required to display a complete waveform. While the acquisition system in the earlier HP 54120 required the microprocessor to oversee each acquisition cycle, the HP 83480 is capable of running many acquisition cycles independently of the CPU. In addition, improvements in the design of the time base allow it to settle in less than 25 μs, compared to 100 μs for the HP 54120. These improvements result in a greater than tenfold throughput improvement over the HP 54120.

The cycle starts after the CPU has programmed a series of delay values into the sequencer memory based on the time-per-division setting of the oscilloscope. These delay values determine the time interval between the arrival of a trigger and the taking of a sample. Once the values have been programmed, the acquisition system continues to take samples at the programmed delay values until stopped or paused by the CPU.

The sampler in the plug-in measures the difference between the input signal's instantaneous amplitude at the sampling instant and a dc offset value programmed by a digital-to-analog converter DAC). This difference is amplified and converted to a bipolar pulse by charge amplifiers and IF filters located in the plug-in. This bipolar pulse signal is fed to the track-and-hold circuits in the mainframe. The charge amplifiers and IF filters in these circuits have been improved over those in the HP 54120 to achieve better than a factor of 2 improvement in noise floor.

The track-and-hold circuits follow the amplitude of the bipolar pulse. When the pulse reaches peak amplitude, the track-and-hold circuit holds the peak analog value. The ADCs convert each track-and-hold circuit's level to a 12-bit digital word. These 12-bit words are then put into a FIFO memory which is read and processed by the CPU.

Trigger and Time Base Systems

The oscilloscope's trigger system and time base play key roles in overall performance. To view the transition of a waveform, the oscilloscope must be syncronized to that transition. This syncronization must be very tight to achieve low jitter and high bandwidth. In the sequential sampling mode, the oscilloscope must trigger 500 times to capture and display 500 points. If the trigger has any jitter or uncertainty when it fires, this will be represented by a smeared waveform on screen. The need for a jitter-free trigger becomes all the more apparent given the fact that the HP 83480's fastest sweep time is 10 picoseconds per division.

The trigger system was leveraged intact from the HP 54120. The heart of the trigger mechanism is a threshold comparator—a custom circuit employing high-frequency hybrid technology. This circuit generates accurate, predictable, and programmable trigger performance that does not require delicate adjustment to yield a stable and jitter-free trigger point. The trigger detects the occurrence of a transition on the selected external trigger input. When the programmable threshold level is crossed, an acquisition cycle is started and the time base goes into action. Each plug-in module can have one trigger input, so up to two separate trigger inputs are available.

Firmware

The firmware system in the HP 83480 is highly leveraged from the HP 54720. Like any oscilloscope, the HP 83480 observes input signals, and in response to a user's request it produces data or screen images that describe these signals. These tasks are broken into five successive actions: signal conditioning, acquisition, data analysis, user interface, and display (Fig. 6).

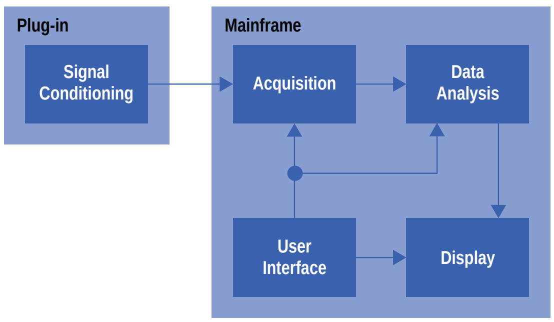

Fig. 6. *HP 83480 firmware block diagram.*

Signal conditioning in the HP 83480 includes the optical-to-electrical conversion in the optical channels and any signal amplification or attenuation that is built into the plug-ins. The sequential sampling acquisition system in the HP 83480 is completely different from the real-time sampling system in the HP 54720, so different drivers are required to control this acquisition system. After the acquisition drivers, the firmware system in the HP 83480 is identical to that of the HP 54720 except for the addition of the specialized measurements added for the communications industry. Measurements that were added for the HP 83480 include time and voltage histograms, more elaborate mask testing, and the ability to measure pulse parameters on multivalued waveforms such as eye diagrams. For details see the article on page 1. One testament to the flexibility of the software system is that histograms, while written for the HP 83480, were incorporated into a maintenance release of the HP 54720 over a year before the HP 83480 was introduced.

Plug-in Module Design

The plug-in modules house the O/E converters, samplers, and vertical channel signal conditioning circuitry. They also include the cabling necessary to interface the trigger hybrid in the mainframe to the instrument front panel. An early design decision the team faced was what sizes of plug-ins to adopt. The mainframe was leveraged from the HP 54720 oscilloscope, which had four input channels and accepted up to four single-slot plug-ins, two double-slot plug-ins, or one four-slot plug-in. Its plug-ins, however, were much simpler than those envisioned for the HP 83480. A single-slot module could not contain all the sampling circuitry, microwave hardware, and digital control circuitry necessary in even the simplest HP 83480 plug-in. The team decided that while the HP 83480 should still have four input channels, acceptable plug-ins would be restricted to two-slot and four-slot modules (no four-slot modules have been introduced to date).

Plug-ins come in two styles: optical and electrical. Optical plug-ins include one optical input channel and one electrical input channel, while electrical plug-ins consist of one or two electrical input channels. Optical measurement bandwidths range from 2 GHz to 30 GHz and electrical measurement bandwidths range from 12.4 GHz to 50 GHz. Plug-ins are also available that provide electrical TDR measurements (see ***Article 3***).

Three optical plug-in modules have been introduced: the HP 83485A, HP 83485B, and HP 83481A. Each optical plug-in module is optimized for particular SONET/SDH transmission rates from 155.52 Mbits/s to 9.95328 Gbits/s. A simplified block diagram of an optical channel is shown in Fig. 7. Each optical channel consists of an optical-to-electrical converter followed by a microwave transfer switch which routes the electrical signal either directly to the microwave sampler or first through an electrical low-pass filter. The overall frequency response of the filtered path consisting of the O/E converter, transfer switch, filter, sampler, various semirigid cables, and the associated mismatch ripple meets the SONET/SDH requirements for a reference receiver. This is not a trivial objective; it requires careful design of the filter frequency response and low VSWR terminations in the associated circuits. In addition, each optical channel includes a built-in average optical power monitor. (For more information on the optical plug-in module design see ***Article 2***)

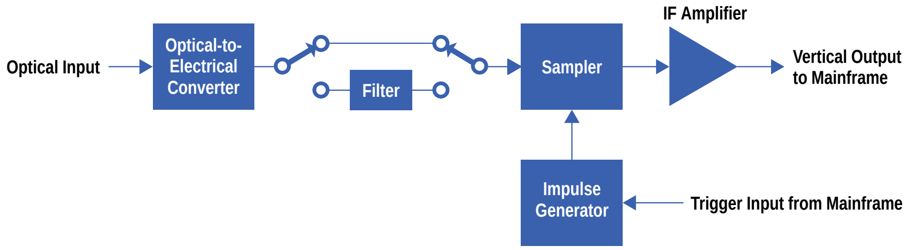

Fig. 7. *Optical plug-in module block diagram.*

Manufacturing

The manufacturing processes for the mainframe and plug-in modules are heavily leveraged from existing processes for the HP 54720 and HP 54120 oscilloscopes. The most significant manufacturing development challenge was the test processes for the optical plug-ins. Frequency response calibration was a particular challenge because of the extremely tight tolerance imposed on the reference receiver by the SONET/SDH standards. HP engineers worked closely with the U.S. National Institute for Standards and Technology (NIST) to implement a test system accurate enough to meet the intent of these standards (see ***Article 4***).

Acknowledgments

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