Jitter Analysis of High-Speed Digital Systems

The HP 71501B jitter and eye diagram analyzer performs industry-standard jitter tolerance, jitter transfer, and jitter generation measurements on Gbit/s telecommunication system components. It can display both the jitter spectrum and the jitter waveform to help determine whether jitter is limiting the bit error ratio of a transmission system.

by Christopher M. Miller and David J. McQuate

Digital communication systems typically consist of a transmitter, some type of communications medium, and a receiver or line terminal unit. Typically, the digital pulses transmitted in these systems are attenuated and dispersed as they propagate through the transmission medium. To overcome signal attenuation along the transmission path, the signal may be reamplified. To overcome both attenuation and dispersion the signal may be regenerated. A regenerator receives the data stream of ones and zeros, extracts the clock frequency, then retimes, reshapes, and retransmits the digital data. Even if regenerators are not employed in the transmission system, the receiver always performs the process of extracting the clock signal to decode the data stream. Any fluctuation in the extracted clock frequency from a constant rate is referred to as jitter.

The International Telegraph and Telephone Consultative Committee (CCITT) has defined jitter as "short-term noncumulative variations of the significant instants of a digital signal from their ideal positions in time." A significant instant can be any convenient, easily identifiable point on the signal such as the rising or falling edge of a pulse or the sampling instant. The time variation in the significant instants of a digital signal is equivalent to variations in the signal's phase. A second parameter closely related to jitter is wander. Wander generally refers to long-term variations in the significant instants. There is no clear definition of the boundary between jitter and wander, but phase variation rates below 10 Hz are normally called wander.

Fig. 1 shows an ideal pulse train compared at successive instants T_n with a pulse train that has some timing jitter. The jitter time function is obtained by plotting the relative displacement in the instants versus time. Typically, the jitter time function is not sinusoidal. The jitter spectrum can be determined by taking a Fourier transform of the jitter time function.

Controlling jitter is important because jitter can degrade the performance of a transmission system by introducing bit errors in the digital signals. Jitter causes bit errors by preventing the correct sampling of the digital signal by a regenerator

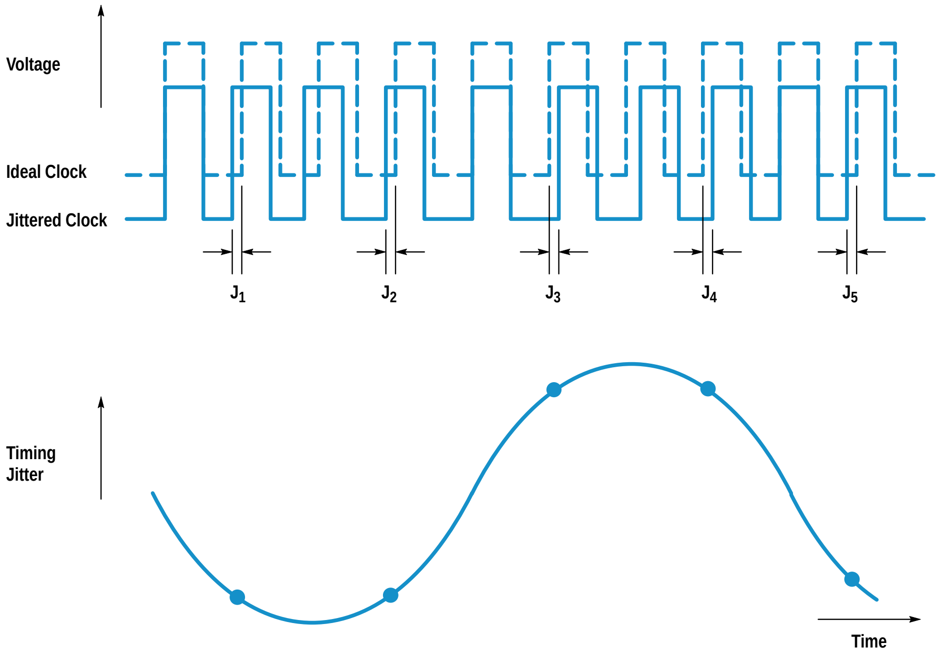


Fig. 1. Jitter time function derived from comparing a jittered clock with an ideal clock.

or a line terminal unit. Jitter can accumulate in a transmission network depending on the jitter generation and transfer characteristics of the interconnected equipment.

Jitter Measurement Categories

In an effort to standardize the high-speed telecommunication systems that are being developed and deployed, standards have been adopted for equipment manufacturers and service providers to use. Two such standards are the synchronous optical network (SONET), a North American standard, and the synchronous digital hierarchy (SDH), an international standard. Both standards are for high-capacity fiber-optic transmission and have similar physical layer definitions. These standards define the features and functionality of a transport system based on principles of synchronous multiplexing. The more popular transmission rates are 155.52 Mbits/s, 622.08 Mbits/s, and 2.48832 Gbits/s. The standards specify the jitter requirements for the optical interfaces with the intention of controlling the jitter accumulation within the transmission system.[1,2] The transmission equipment specifications are organized into the following categories: jitter tolerance, jitter transfer, and jitter generation.

Jitter tolerance is defined in terms of an applied sinusoidal jitter component whose amplitude, when applied to an equipment input, causes a designated degradation in error performance. Equipment jitter tolerance performance is specified with jitter tolerance templates. Each template defines the sinusoidal jitter amplitude-versus-frequency region over which the equipment must operate without suffering a designated degradation in error performance. The difference between the template and the tolerance curve of the actual equipment represents the operating jitter margin and determines the pass or fail status.

Each transmission rate typically has its own input jitter tolerance template. In some cases, there may be two templates for a given transmission rate to accommodate different regenerator types. Jitter amplitude is traditionally measured in *unit intervals* (UI), where 1 UI is the phase deviation of one clock period.

Jitter transfer is the ratio of the amplitude of an equipment's output jitter to an applied input sinusoidal jitter component. The jitter transfer function is also specified for each transmission rate and regenerator type. Jitter transfer requirements on clock recovery circuits specify a maximum amount of jitter gain versus frequency up to a given cutoff frequency, beyond which the jitter must be attenuated. The jitter transfer specification is intended to prevent the buildup of jitter in a network consisting of cascaded regenerators.

Jitter generation is a measure of the jitter at an equipment's output in the absence of an applied input jitter. Jitter generation is essentially an integrated phase noise measurement and for SONET/SDH equipment is specified not to exceed 10 mUI root mean square (rms) when measured using a high-pass filter with a 12-kHz cutoff frequency. A related jitter noise measurement is output jitter, which is a measure of the jitter at a network node or output port. Although similar to jitter generation, the output jitter of the network ports is specified in terms of peak-to-peak UI in two different bandwidths.

Jitter Measurement Techniques

Although these jitter measurements are made on digital waveforms, the tests themselves tend to be analog in nature. The most frequently encountered techniques to measure jitter usually employ either an oscilloscope or a phase detector. It is worth noting that there are additional jitter measurements that deal with asynchronous data being mapped into the SONET/SDH format. These tests examine the jitter introduced by payload mapping and pointer adjustments, and are performed by dedicated SONET/SDH testers.

Intrinsic data jitter, intrinsic clock jitter, and jitter transfer can be directly measured with a high-speed digital sampling oscilloscope. As shown in Fig. 2a, a jitter-free trigger signal for the oscilloscope is provided by clock source B, whose frequency reference is locked to that of clock source A. Clock source A, which is modulated by the jitter source, drives the pattern generator. The pattern generator supplies jittered data for the jitter transfer measurement to the device under test (DUT). The jittered input and output waveforms can be analyzed using the built-in oscilloscope histogram functions. The limitations of the oscilloscope measurement technique are the following. The maximum jitter amplitude that can be measured is limited to 1 UI peak to peak. Above this level, the eye diagram is totally closed. Secondly, this technique offers poor measurement sensitivity because of the inherently high noise level resulting from the large measurement bandwidth involved. Third, the technique does not provide any information about the jitter spectral characteristics or the jitter time function. Finally, the technique requires an extra clock source to provide the oscilloscope trigger signal.

Many of the limitations of the sampling oscilloscope technique can be addressed by using a phase detector. The phase detector, in Fig. 2b, compares the phase of the recovered clock from the device or equipment under test with a jitter-free clock source. The output of the phase detector is a voltage that is proportional to the jitter on the recovered clock signal. The range of the phase detector can be extended beyond 1 UI by using a frequency divider. Intrinsic jitter is measured by connecting the output of the phase detector to an rms voltmeter with appropriate bandpass filters. A low-frequency network analyzer can be connected to the output of the phase detector to measure jitter transfer.

The phase detector method forms the basis for most dedicated jitter measurement systems. It is relatively easy to implement and provides fast intrinsic jitter measurements. However, there are several limitations. A jitter measurement system employing this technique usually consists of dedicated hardware, which only functions at specific transmission rates. In addition, the accuracy of the jitter transfer measurement with a network analyzer may be insufficient to guarantee that the specification in the standard is being met. Finally, the technique requires an additional clock source as a reference for the phase detector.

Jitter and Eye Diagram Analyzer

The HP 71501B jitter and eye diagram analyzer is a sampler-based instrument that offers a general-purpose solution to these jitter measurement requirements. To perform jitter

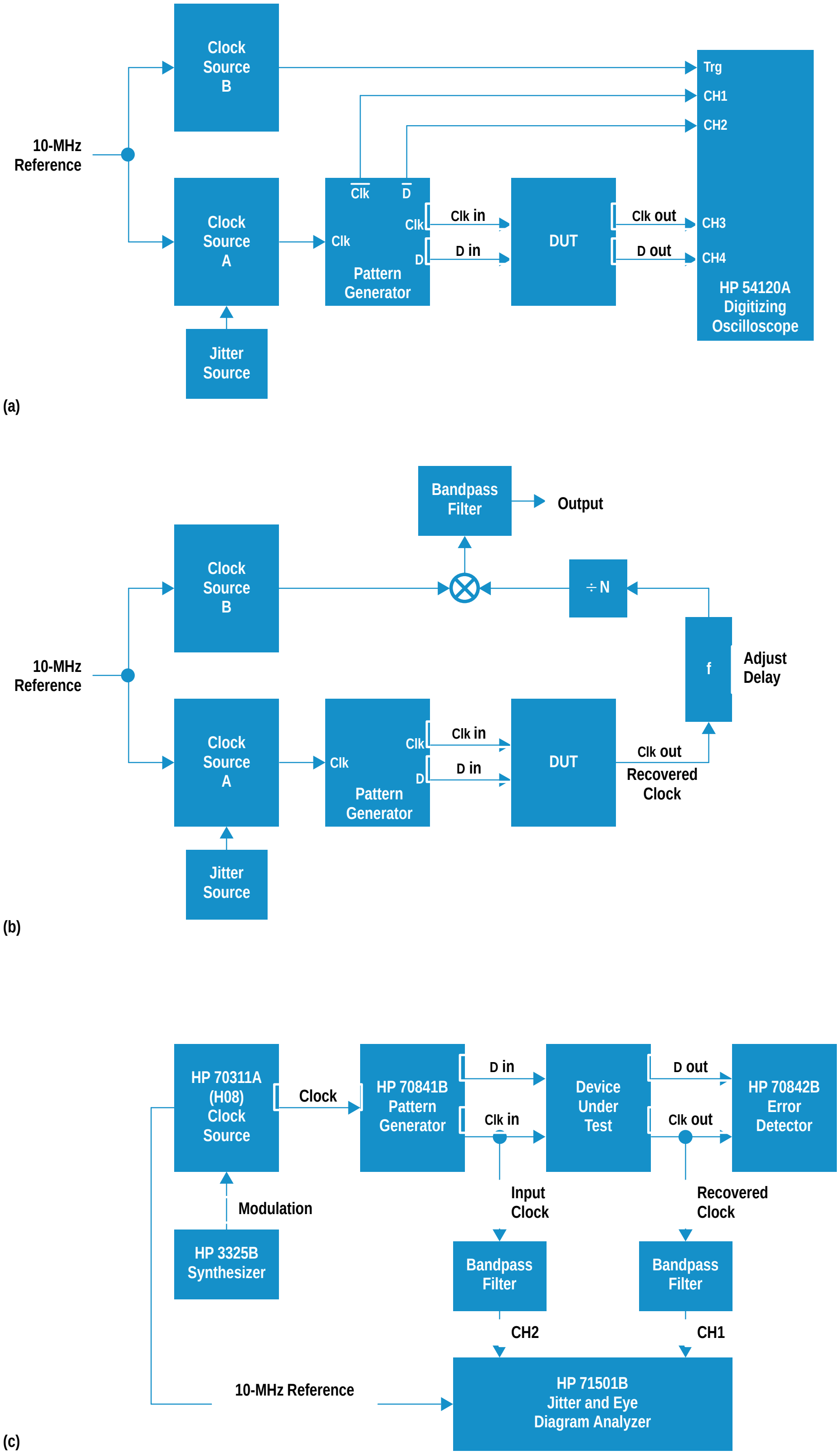


Fig. 2. (a) Oscilloscope-based jitter measurement system. (b) Phase-detector-based jitter measurement system. (c) HP 71501B jitter measurement system.

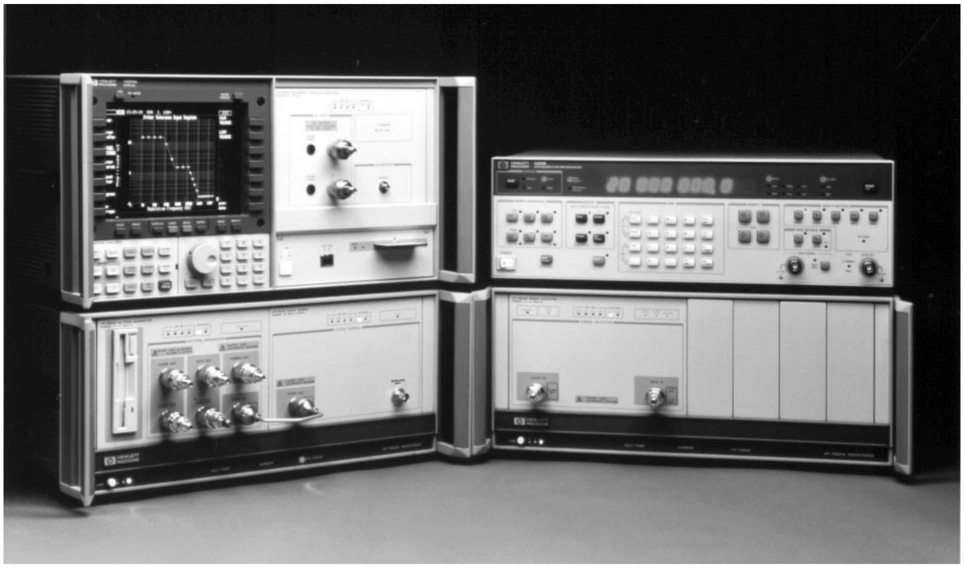


Fig. 3. HP 71501B jitter measurement system.

measurements, the HP 71501B combines the HP 70820A microwave transition analyzer module,[3] the HP 70004A color display and mainframe, and the HP 70874B jitter personality. The personality is stored on a 256K-byte ROM card and can be downloaded into the instrument. Shown in Fig. 3 is a photograph of the HP 71501B-based jitter measurement system. The system configuration, shown in Fig. 2c, includes an HP 70841B 3-Gbit/s pattern generator, an HP 70842B error detector, an HP 70311A Option H08 clock source, and an HP 3325B synthesizer, which serves as the jitter modulation source. The downloaded jitter personality allows the the HP 71501B to take control of all the other instruments in the jitter measurement system and to coordinate the measurements. This jitter measurement capability has been recently extended to 12 Gbits/s with the introduction of the HP 70843A error performance analyzer. Also, sophisticated eye diagram measurements can be made when the eye diagram personality is downloaded into the instrument.[4]

Sampler-based instruments like the HP 71501B typically operate by taking time samples of the data, then analyzing it using digital signal processing techniques. The HP 71501B has two input channels which allow it to analyze jitter transfer. Each signal processing channel can sample and digitize signals from dc up to 40 GHz, so the jitter measurement process is inherently frequency-agile. As shown in the block diagram in Fig. 4, input signals to each channel are sampled by a microwave sampler at a rate between 10 MHz and 20 MHz. The precise sample rate is set based on a determination of the incoming signal frequency and the type of measurement being made. The output of the samplers is fed into the dc-to-10-MHz intermediate frequency (IF) sections. The IF sections contain switchable low-pass filters and step-gain amplifiers. The dc components of the measured signal are tapped off ahead of the microwave sampler and summed into the IF signal separately. The output of the IF sections is sampled at the same rate as the input signal and then converted to a digital signal by the analog-to-digital converters (ADC).

Once the signals are digitized, they are fed into the buffer memories. These buffers hold the samples until the trigger

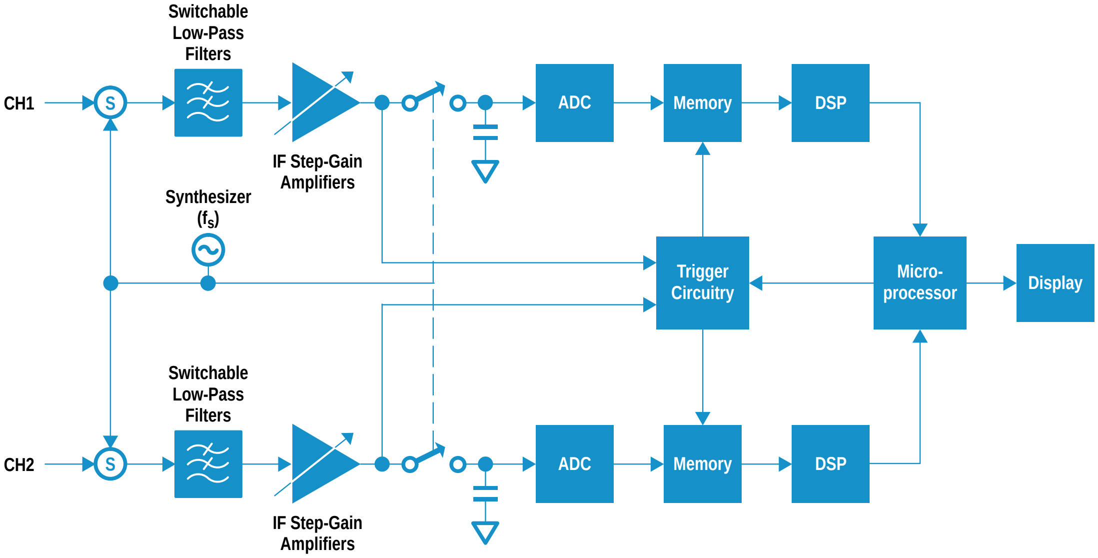


Fig. 4. Simplified block diagram of the HP 71501B jitter and eye diagram analyzer.

point is determined. By triggering on the IF signal, the HP 71501B is able to trigger internally on signals with fundamental frequencies as high as 40 GHz. Once the trigger point has been determined and all the necessary data has been acquired, the appropriate data is sent to the digital signal processing (DSP) chips. The time data in the trace memory buffer that is sent to the DSP chip has an FFT performed on it. With the time data now converted into the frequency domain, IF and RF corrections are applied to the data. The IF corrections compensate for nonidealities in the analog signal processing path. The RF corrections compensate for roll-off in the microwave sampler conversion efficiency as a function of incoming signal frequency. A Hilbert transform is then performed on the corrected frequency data to generate a quadrature set of data, and an inverse FFT is performed. This quadrature set of time-domain data is combined with the original sampled time data to form a complex-valued representation of the signal called the *analytic signal.* The analytic signal simplifies the manipulation and analysis of modulated waveforms.[5] Specifically, in this application, it is used to recover the jitter time function.

The HP 71501B can make and display measurements of the frequency spectrum or time-domain waveform of a jittered clock signal. It can also demodulate the jittered clock signal to display and perform measurements on the jitter spectrum or jitter time function. Fig. 5a shows a 2.48832-GHz clock signal displayed in the time domain. The jitter function in this example is a sinusoid at a 10-kHz rate with an amplitude that corresponds to a phase deviation of 0.25 UI peak-to-peak. This display is similar to what one would observe on a high-speed oscilloscope with the appropriate trigger signal. Fig. 5b shows the clock spectrum with jitter sidebands. This display is similar to what would be observed on an RF spectrum analyzer. Finally, shown in Fig. 5c are simultaneous frequency-domain and time-domain displays of the demodulated jitter function. As will be shown later, the measurement technique used by the HP 71501B depends on the spectral content and magnitude of the jitter time function, and the type of measurement being performed.

Measuring Sinusoidal Jitter

As previously stated, jitter is essentially phase modulation. For small amounts of sinusoidal phase modulation, a single pair of sidebands is observed, which are separated from the carrier (clock frequency) by the modulation frequency. For small values of modulation index, the magnitude of the sidebands is linearly proportional to the modulation index. As the modulation index increases additional sidebands appear and the relationship between modulation index and sideband magnitude becomes nonlinear. The amplitude of the nth sideband relative to the magnitude of the unmodulated carrier can be calculated using the nth ordinary Bessel function, with the modulation index β as an argument.

$$A_n = J_n(\beta),$$

$$\beta = \pi \times \mathrm{UI}.$$

The modulation index is an indicator of the number of significant sidebands, significant being greater than −20 dB relative to the unmodulated carrier. The bandwidth BW of a phase modulated carrier, expressed as a function of the

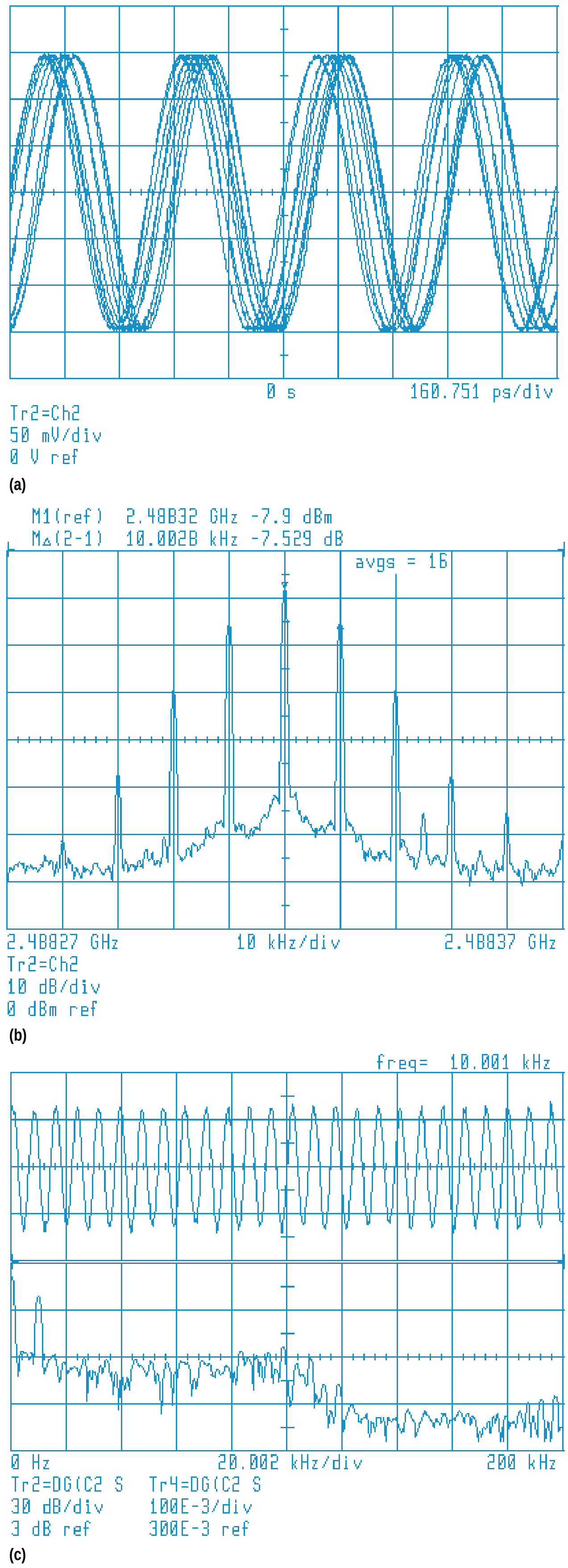


Fig. 5. (a) Jittered 2.48832-GHz clock signal. (b) Spectrum of the jittered clock signal. (c) Demodulated 10-kHz jitter waveform and spectrum.

modulation index and the modulation frequency f_{mod}, can be approximated using Carson's rule:

$$BW \approx 2f_{mod}(1 + \beta).$$

Theoretically, a bandwidth-limited signal can be accurately reconstructed if the sample rate is more than twice the signal's bandwidth. Since the HP 71501B's maximum sampling frequency is 20 MHz, accurate, unaliased sampled representations can be obtained of signals whose bandwidth is less than 10 MHz. The instrument's microwave sampler converts the jittered signal at the clock frequency, f_{signal}, down into the IF by mixing the signal frequency with a harmonic of the sample frequency, f_{sample}. This harmonic number is referred to as the comb number, N. The minimum comb number is:

$$N_{minimum} = \text{ceiling}\{f_{signal}/20\text{ MHz}\},$$

where ceiling{x} is the smallest integer greater than x. This integer comb number is then used to compute the sample frequency for the given signal frequency with the following relationship:

$$f_{sample} = f_{signal}/[N + (\text{number of cycles}/\text{number of trace points})].$$

The jittered signal at the clock frequency would be mixed down to zero frequency in the IF without the term cycles/trace points, which is used to place the down-converted signal in the IF without having the sidebands fold over. In Fig. 6, an example is shown for a clock frequency of 2.48832 GHz, a minimum comb number of 125, trace points equal to 1024, and cycles equal to 256. The corresponding sample frequency is 19.866826 MHz. The effective IF bandwidth is one-half the sample frequency or 9.939413 MHz in this case, and the down-converted signal is centered in the IF.

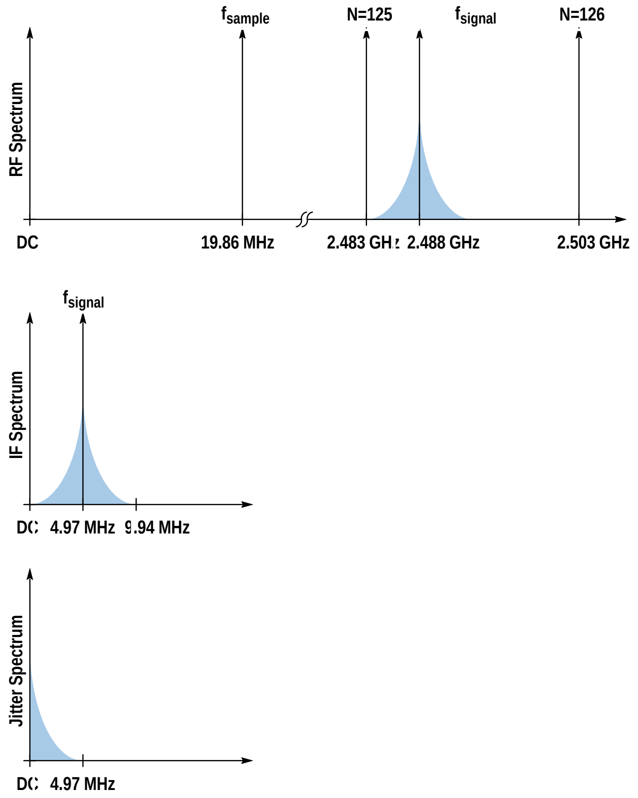


Fig. 6. Example RF, IF, and jitter spectra for a 2.48832-GHz jittered clock signal and an HP 71501B sample frequency of 19.866826

For these signals, the phase modulation waveform can be determined using the built-in `DEG` math function based on the analytic signal. The peak-to-peak jitter can be measured directly on this demodulated waveform. However, to improve the measurement signal-to-noise ratio, particularly for low levels of sinusoidal phase modulation, a discrete Fourier transform of the modulation waveform can be performed. The peak jitter can be determined from the magnitude of the spectral component corresponding to the modulation frequency. This component represents the energy in a small frequency band whose width is set by the window function used in calculating the transform. A flat-top window is used in the HP 71501B for single-frequency sinusoidal jitter measurements. This window function effectively serves as a resolution bandwidth filter that reduces the random noise. The resolution bandwidth RBW of the window function can be determined from:

$$RBW = \text{Window Factor} \times f_{sample}/\text{number of trace points},$$

where the window factor is 3.60 for a flat-top window. For a fixed sample rate, as the modulation frequency is reduced, the corresponding spectral component in the Fourier transform moves closer to that of the zero-frequency component. In the limit, the window functions of these two components overlap, and the magnitude of the modulation rate spectral component is contaminated. To counter this effect the comb number can be increased, reducing the sample rate and moving the modulation-frequency component away from the zero-frequency component. However, reducing the sample rate decreases the effective IF bandwidth, and thus the measurable signal bandwidth. Based on the specified jitter magnitude, the maximum comb number can be determined using the following relationship, with f_{sample} set equal to twice Carson's bandwidth:

$$N_{maximum} = \text{INT}\left\{\frac{f_{signal}}{4f_{mod}[1 + (\pi \times \text{UI})]} - \frac{\text{number of cycles}}{\text{number of trace points}}\right\}.$$

As long as the sample frequency is greater than twice the down-converted signal's bandwidth, the transform measurement is performed. If not, the sample frequency is increased to meet the requirements of Carson's rule and the measurement is made directly on the modulation waveform. Typically, when this occurs, the specified jitter magnitude is quite large and measurement uncertainty resulting from random noise can be ignored. Often, the clock frequency, jitter modulation frequency, and magnitude are specified either by the requirements in the standard or by the customer, and in such cases the HP 71501B uses this information to determine the optimum measurement mode.

When the signal's bandwidth exceeds 10 MHz, the instrument's maximum IF bandwidth, the down-converted signal becomes aliased and the phase modulation waveform cannot be directly obtained. However, it is still possible to determine the modulation index of signals containing sinusoidal jitter. In this case, the instrument measures the signal's RF spectrum directly, setting the sample rate such that the carrier and first-order sidebands fall at convenient places in the IF band. The magnitude of the carrier is measured, and the average of the magnitudes of the first order-sidebands is determined. Using the average of the upper and lower first-order sidebands significantly reduces any effect that incidental amplitude modulation (AM) may have on the phase modulation (PM) measurement. The modulation index β is calculated by numerically solving:

$$\frac{A_1}{A_0} = \frac{J_1(\beta)}{J_0(\beta)},$$

where A_1 is the average of the magnitudes of the first pair of sidebands, A_0 is carrier magnitude, and J_0 and J_1 are Bessel functions. Since only the carrier and first-order sidebands are measured, this technique can determine the modulation index for jitter levels up to that at which J_0 goes through its first null. This occurs at a jitter amplitude of 0.76 UI, which is about a factor of five larger than the jitter level of 0.15 UI specified in the standards for modulation frequencies that approach or exceed the instrument's maximum IF bandwidth of 10 MHz.

Jitter Tolerance and Jitter Transfer

Jitter tolerance and jitter transfer are both stimulus-response measurements. At each jitter modulation frequency, the amount of specified jitter is applied to the device under test (DUT), and its response is observed. As shown in Fig. 2c, The HP 71501B monitors the jitter level on the clock output of the pattern generator on Channel 2. The instrument uses its various sinusoidal jitter measuring techniques to adjust the amplitude of the HP 3325 synthesizer to calibrate the jitter level on the clock source to typically better than 1% accuracy. The jitter on the clock source is then transferred equally to both the data and clock outputs of the HP 70841B pattern generator. The jittered data output is applied to the DUT. The HP 71501B includes built-in input jitter amplitude-versus-frequency templates corresponding to OC-12, OC-48, STM-4, and STM-16 transmission requirements. In addition, the user can create and edit custom input templates, which can be saved to and retrieved from a RAM card. In Fig. 7, the maximum settable jitter amplitude is shown for the system relative to the requirement of the OC-48 input template. The maximum measurable jitter of the HP 71501B is 30 UI peak-to-peak for the unaliased measurements, and 0.7 UI peak-to-peak for the aliased measurements. Over most of the jitter frequency range, the maximum jitter amplitude is limited by the phase modulation capability of the HP 70311A clock source. In any case, these maximum limits are well in excess of the requirements of the standard template.

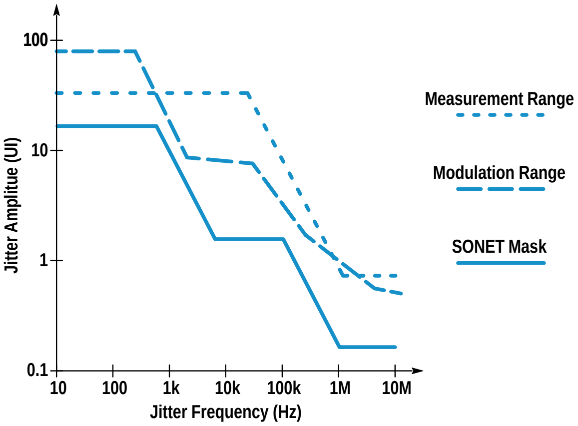


Fig. 7. Maximum sinusoidal jitter measurement range at 2.48832 GHz.

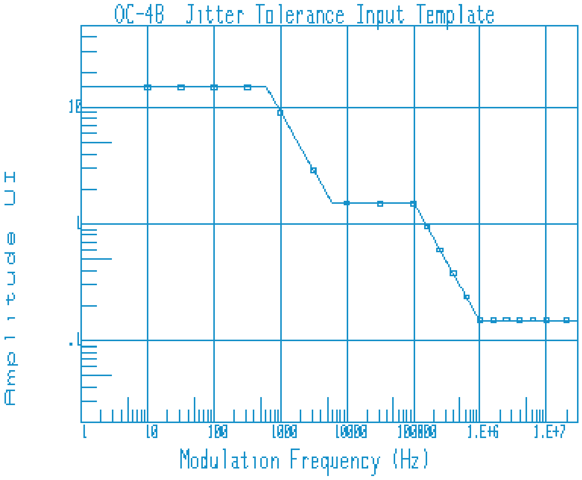


Fig. 8. OC-48 jitter tolerance measurement on a DUT.

In the jitter tolerance test, the error performance of the DUT is monitored by the 70842B error performance analyzer. The aim of the test is to determine if the DUT's error performance is degraded by jitter at a specified frequency and amplitude level. Fig. 8 shows the result of a jitter tolerance measurement made on a clock and data recovery circuit. The input template was the standard template for OC-48, which corresponds to a clock rate of 2.48832 Gbits/s. Boxes correspond to measurement points that passed. Xs indicate measurement points that failed. Either bit errors or a particular error rate can be selected as the failure criterion.

In the jitter transfer test, the jitter on the DUT's recovered clock output is monitored on channel 1 of the HP 71501B and compared to the input jitter on channel 2. The ratio is then computed. This test is required to ensure that once installed in a system, these devices won't significantly increase jitter in any part of the spectrum. A cascade of similar devices, each with just a small increase in jitter, could result in an unmanageable jitter level. The standards specify a maximum value of jitter transfer of only 0.1 dB up to the specified bandwidth of the clock recovery circuit. This level has been difficult to measure accurately. The HP 71501B with its two matched input channels typically makes this measurement with an accuracy of hundredths of a dB. Shown in Fig. 9 is a jitter transfer measurement made on a DUT at OC-48. The solid line corresponds to the maximum specified jitter level at a given frequency. The boxes correspond to measurement points that passed. Xs correspond to measurement points that failed. Failures, if they occur, typically occur near the bandwidth limit of the clock recovery circuit.

Jitter Generation and Output Jitter

Both the jitter generation and output jitter tests are measurements of intrinsic random phase noise in a specific bandwidth with no external jitter applied. The HP 71501B uses the same measurement procedure for both jitter generation and output jitter, calculating both the peak-to-peak and rms

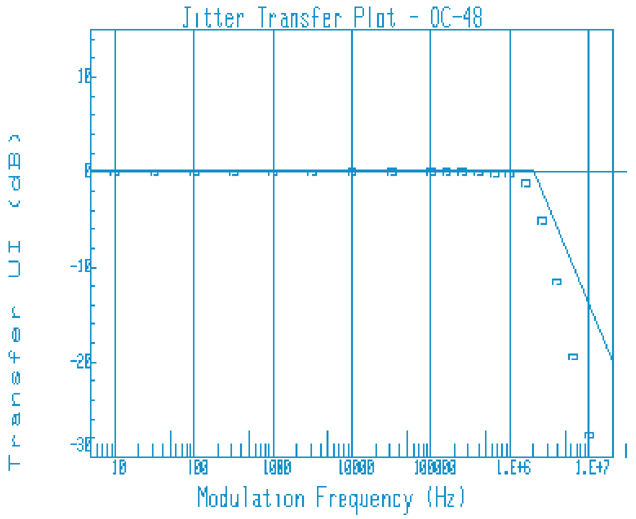


Fig. 9. OC-48 jitter transfer measurement on a DUT.

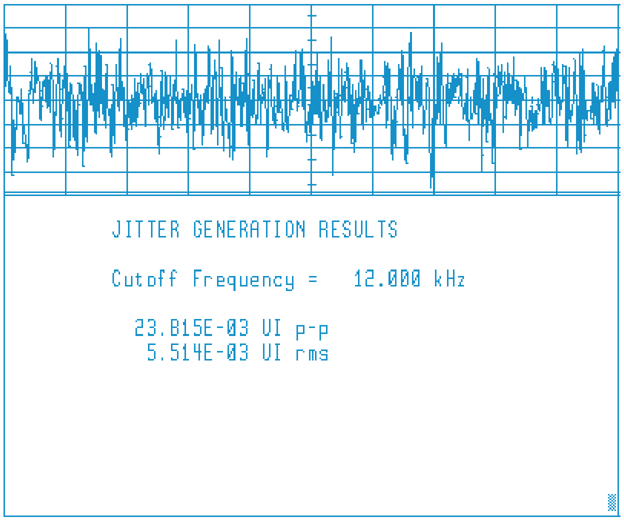
jitter values. The upper end of the measurement frequency range is set by the hardware bandpass filter, shown in Fig. 2c, whose center frequency is equal to the clock rate. The low-frequency limit is implemented in the following manner. For each instrument sweep, the phase noise waveform is computed and an FFT is performed. A high-pass filter function is implemented by multiplying the appropriate elements of the Fourier transform by zero. The sample frequency is chosen so that an integer number of zeroed elements comes within the chosen accuracy of 5% for the filter cutoff frequency. This results in a sample frequency that is approximately 100 times the cutoff frequency. Since aliasing will occur if the signal bandwidth exceeds half the sample frequency, the amplitude of the jitter function is limited so that the resulting bandwidth is less than 50 times the cutoff frequency. By setting the bandwidth in Carson's rule to 50 times the cutoff frequency and working backwards the maximum measurable peak-to-peak UI as a function of frequency can be determined:

$$\mathrm{UI}_{\mathrm{max}}(\text{peak-to-peak}) = \frac{1}{\pi} \times \left(\frac{25f_{\mathrm{cutoff}}}{f} - 1\right).$$

Up to 7.6 UI peak-to-peak can be measured at the high-pass cutoff frequency, with the measurable limit decreasing as 1/f at higher frequencies. The standards specify maximum limits of 0.15 UI peak-to-peak and 1.5 UI peak-to-peak for an entire bandwidth, which affords a comfortable amount of measurement headroom, as long as the intrinsic jitter spectrum falls off as 1/f or faster. Finally, the bandlimited result is transformed back into the time domain, where the peak positive and negative phase excursions are noted and the squares of all the samples are summed. When the requested number of sweeps has been completed, the rms value is calculated from the sum of the squares. Shown in Fig. 10 is a jitter generation measurement performed on an OC-48 clock recovery circuit. The specified cutoff frequency is 12 kHz and the measurement limit is 10 mUI rms.

Summary

Jitter measurements on components of high-speed telecommunication systems are necessary to ensure low-error-rate transmission and are required by the industry standards that define these systems. The HP 71501B jitter and eye diagram analyzer was designed in response to customer needs to make these measurements at the high transmission rates currently employed in optical systems. The HP 71501B can perform the industry-standard jitter tolerance, transfer, and generation measurements. In addition, its measurement technique is frequency-agile, allowing measurements to be made at proprietary transmission rates. Finally, its diverse measurement capability allows it to be used for diagnostics and jitter analysis.



```
JITTER GENERATION RESULTS

Cutoff Frequency =   12.000 kHz

  23.815E-03 UI p-p
   5.514E-03 UI rms
```

Fig. 10. OC-48 jitter generation measurement on a DUT.

Acknowledgments

The jitter analysis measurement capability was a collaboration between Hewlett-Packard's Lightwave Operation in Santa Rosa, California and Queensferry Telecommunications Operations in South Queensferry, Scotland. Initially, as a response to customer measurement needs, John Domokos wrote a preliminary application note with the help of John Wilson. Greg LeCheminant and Geoff Waters obtained additional market inputs that went into the product definition. Thanks go to Steve Peterson and John Wendler for their useful technical inputs. Finally, the jitter measurement personality was coded by Mike Manning, a software contractor from Hamilton Software.

References

1. *Digital line systems based on the synchronous digital hierarchy for use on optical fibre cables,* CCITT Recommendation G.958, 1990.

2. *Synchronous Optical Network (SONET) Transport Systems: Common Generic Criteria,* Bellcore TA-NWT-00253, 1990.

3. D.J. Ballo and J.A. Wendler, "The Microwave Transition Analyzer: A New Instrument Architecture for Component and Signal Analysis," *Hewlett-Packard Journal,* Vol. 43, no. 5, October 1992, pp. 48-62.

4. C. M. Miller, "High-Speed Digital Transmitter Characterization Using Eye Diagram Analysis," *Hewlett-Packard Journal,* Vol. 45, no. 4, August 1994, pp. 29-37.

5. M. Dethlefsen and J. A. Wendler, "Design Considerations in the Microwave Transition Analyzer," *Hewlett-Packard Journal,* Vol. 43, no. 5, October 1992, pp. 63-71.