Anritsu Advancing beyond

Vector Network Analyzer

Selecting the Appropriate Measurement Frequency Bandwidth in the Evaluation of High-Speed Digital Circuits

Introducing high-speed digital transmission technologies, such as PCI Express® (PCIe®) and USB, has dramatically improved communication speeds and data processing performance. These technologies play an essential role in areas such as AI computing, automotive technology, and wireless and optical networks, including real-time data analysis and prediction.
High-speed digital transmission is supported by high-frequency printed circuit boards, semiconductors such as AI chips and ASICs, electrical/optical wiring, and connectors. In high-speed digital systems, as the frequency of the digital signals increases, the signals become more susceptible to degradation, primarily due to factors like the high-frequency loss properties of the transmission line materials. Furthermore, jitter (the term given to fluctuations in the digital signal timing), crosstalk (signal leakage from adjacent signal or bus lines), and deterioration of eye patterns may make it difficult to ensure sufficient operating margins for these high-speed digital systems. Therefore, when designing high-speed digital circuits, it is necessary to verify the frequency characteristics, such as impedance and S parameters, as well as the loss characteristics of the circuit, to prevent degradation of the quality of the digital signal. To do so, a Vector Network Analyzer (VNA) can be used.

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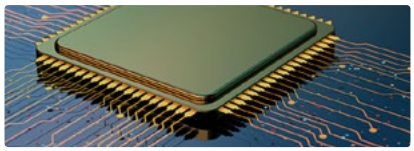
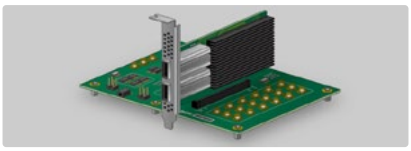
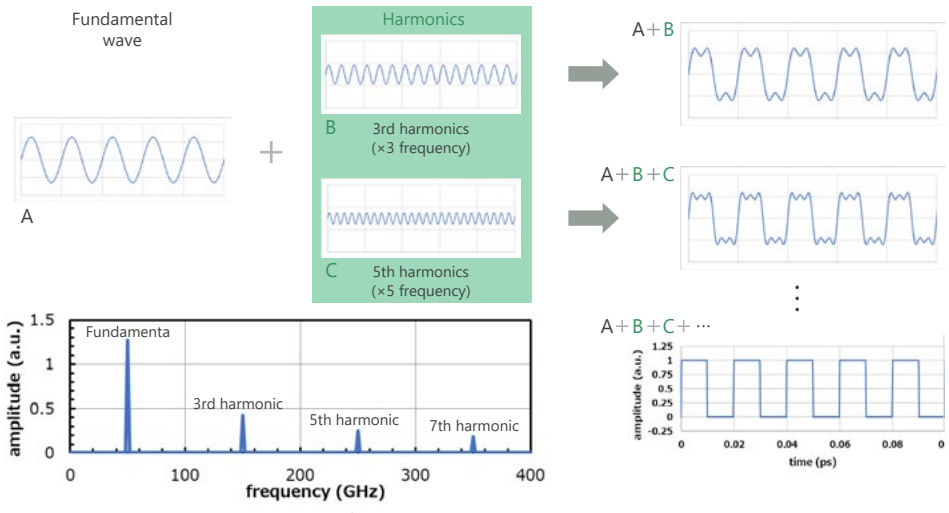




Frequency Components of Digital Signals

In general, digital signals are expressed as square (rectangular) waves. As shown in Figure 1, an ideal square wave can be expressed by superimposing an infinite number of frequency components, such as the 3rd and 5th harmonics, on top of the fundamental wave. These harmonics are necessary to accommodate the rapid changes in the square wave. For this reason, **when evaluating the frequency characteristics of a digital signal, engineers need to consider those harmonics with higher frequencies as well as the fundamental wave frequency**.



Frequency spectrum of a square wave　　Ideal square wave

Figure 1 Frequency Components of Digital Signal.

How to Choose the Appropriate Measurement Bandwidth

Harmonics, which are the frequency components of a digital signal (such as a square wave), continue indefinitely. As such, it is not realistic to evaluate them over an infinite frequency range. Even when the evaluation is performed within a finite frequency range, there are only a limited number of VNAs that can handle up to the 7th or 9th harmonics of high-speed digital signals. Therefore, those harmonics with a frequency of about 3 to 5 times greater than that of the fundamental wave are addressed in practical digital signals.

Next, this document describes the appropriate measurement frequency bandwidth using the non-return-to-zero (NRZ) and PAM4 (Pulse Amplitude Modulation, 4-level) modulation formats as examples. Table 1 lists the technical terms associated with determining the measurement bandwidth.

Table 1 Technical Terms.

Terms	Description	Unit
Data Rate/Bit Rate	The data rate represents the number of bits transmitted per second.	bps, b/s
Symbol Rate/Baud Rate	The symbol rate represents the number of state changes, such as from 0 to 1 or from 1 to 0, per second.	baud
Nyquist Frequency	The Nyquist frequency is half of the symbol rate. It corresponds to the frequency of the fundamental wave shown in Figure 1.	Hz

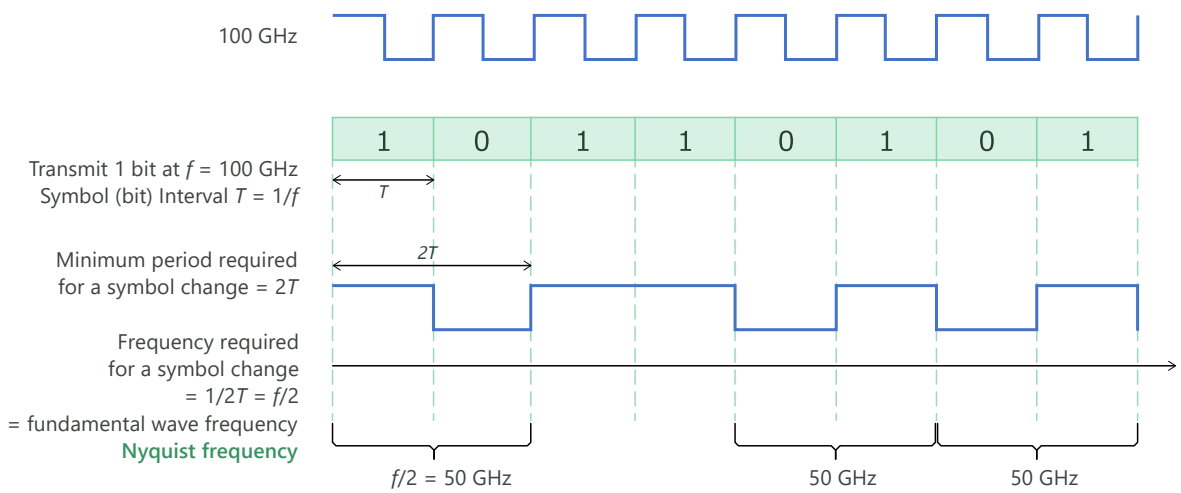
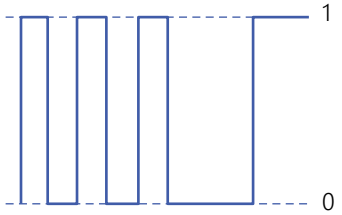
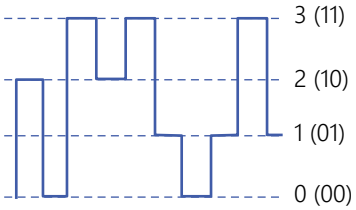


Figure 2 Relation Between Symbol Rate and Nyquist Frequency (NRZ, 100 Gbps/100 Gbaud).

Explain that half of the symbol rate of a digital signal is the Nyquist frequency. The NRZ shown in Figure 2 is a signal that holds a value of 1 or 0 for a certain amount of time (*T*). One symbol represents one bit. This results in the same value for the data rate and the symbol rate. In the example with a symbol rate of 100 Gbaud, symbols are sent at a frequency of f = 100 GHz. Here, the time interval T in which the symbol is transmitted is the reciprocal of f, $T = 1/f$. Since it takes time for two symbols to change, its minimum period is $2T$. The reciprocal of this period is the frequency required for the symbol change, which is $1/2T$ = 50 GHz. This frequency, 50 GHz, is the lowest frequency component of the NRZ, which is the fundamental wave frequency or the Nyquist frequency. In other words, half of the symbol rate is the Nyquist frequency. Note that the Nyquist frequency is defined in the sampling theorem as the maximum frequency at which the original signal can be accurately restored.

Table 2 Comparison Between NRZ and PAM4.

Modulation Format	NRZ	PAM4
Signal Waveform		
Data Rate	100 Gbps	200 Gbps
Symbol Rate	100 Gbaud	100 Gbaud
Nyquist Frequency	50 GHz	50 GHz

PAM4 signals represent 2 bits per symbol. PAM4 transmits data in four different states, such as from 0 to 2 or from 3 to 1, doubling the data rate within the same bandwidth. As a result, half of the PAM4 data rate is the symbol rate. For example, if the PAM4 data rate is 200 Gbps, the symbol rate is 100 Gbaud, and the Nyquist frequency is 50 GHz.

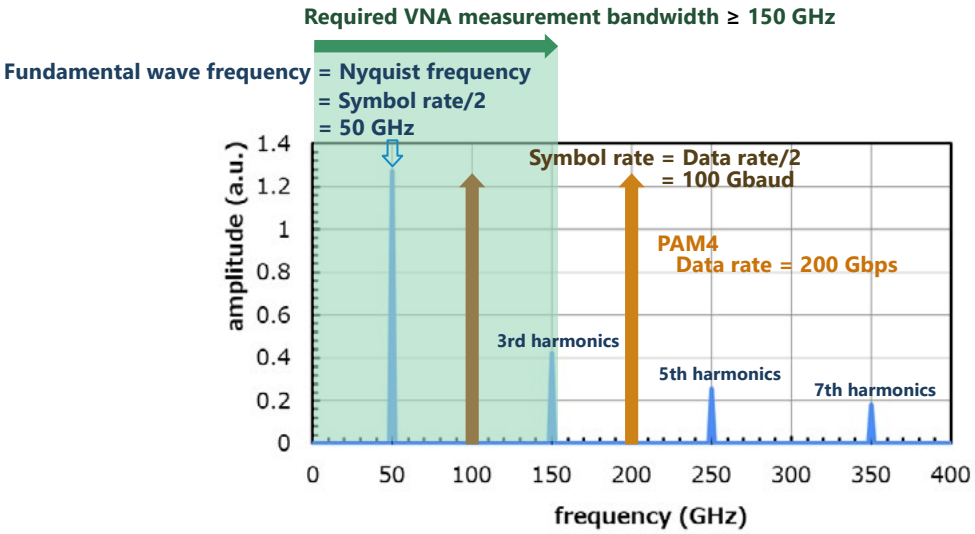


Figure 3 VNA Measurement Bandwidth Including up to 3rd Harmonics (PAM4, 200 Gbps).

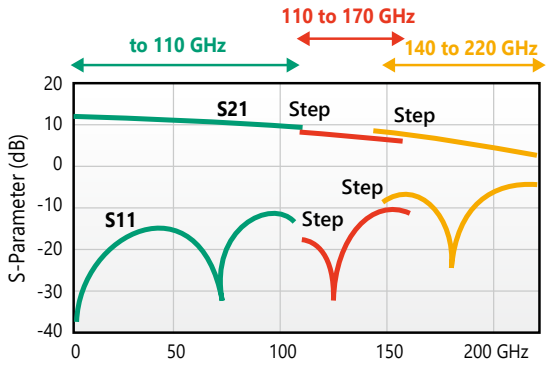
For this reason, **a vector network analyzer with three times the Nyquist frequency, i.e., a measurement frequency bandwidth of 150 GHz or greater, is mandatory to evaluate the frequency characteristics of NRZ with a data rate of 100 Gbps and PAM4 with a data rate of 200 Gbps, including up to the 3rd harmonics**.

As such, upon evaluating the frequency characteristics of high-speed digital circuits, the measurement frequency bandwidth of the vector network analyzer should be set in reference to the Nyquist frequency of the digital signal.

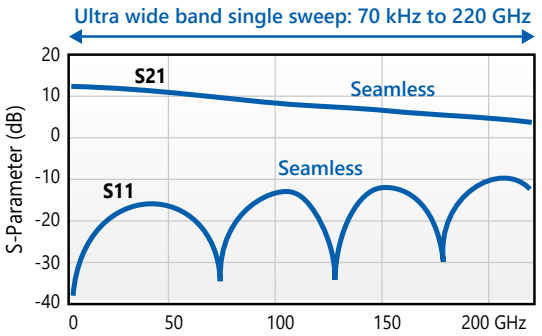
Wideband Characteristics Evaluation

The evaluation of frequency band characteristics above 100 GHz is key to research and development related to ultrafast digital devices. However, VNA systems using conventional waveguide-based millimeter-wave extension modules incurred issues with the need for physical module replacement and the associated recalibration, as well as the data discontinuities (steps) that occur between bands.

Anritsu's VNA VectorStar ME7838 Series and MPI Corporation testing solutions can sweep from 70 kHz to 220 GHz in a single pass, eliminating these tedious tasks and acquiring accurate S-parameters with continuity. This contributes to dramatically shortening R&D cycle times.



VNA System Using Conventional Waveguide-Based Millimeter-Wave Extension Modules



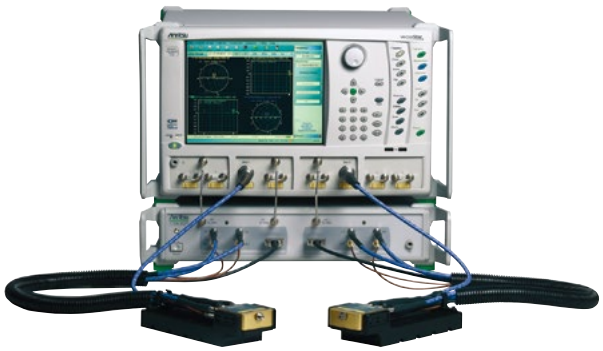
Anritsu and MPI Corporation Solutions

VNA capable of sweeping ultra-wideband from 70 kHz to 220 GHz
No need to replace waveguide modules.
No splicing is required. No steps

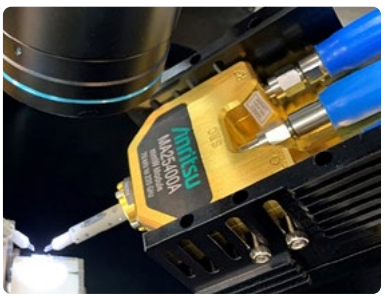
Figure 4 Evaluation of Wideband Frequency Response.

Wideband Frequency Response Verification Solution

Anritsu's wideband VNA VectorStar ME7838 series covers the frequency range from 70 kHz to 220 GHz. Connecting the 220-GHz mmWave module MA25400A to the MPI probe tip allows users to evaluate the wideband frequency response in a single sweep. In addition, it can be extended to measurements up to 1.1 THz in the millimeter-wave band.



VNA VectorStar ME7838 Series



220 GHz Millimeter Wave Module (MA25400A) and MPI Probe Tip

For details of the ME7838 Series

For details of the video and webinar on this solution