Signal Integrity: Frequency Range Matters!

By Jon Martens and Bob Buxton

Introduction

Higher data rates introduce new challenges for test solutions. There are several 20+ Gbit/s high speed standards (Table 1) that are driving the upper end of the test spectrum to 70 GHz and even 110 GHz. Along with the design trade-offs related to choices of vias, stackups, and connector pins, accurate measurements are needed to better understand new challenges related to conductor skin effects and dielectric losses on PC boards. For many of these measurements, it is necessary to collect data that includes higher value harmonic frequencies.

Standard	Data Rate	Number of Lanes
CEI-25G-SR	19.90 to 28.05 Gbit/s	1 to N
CEI-25G-LR	19.90 to 25.80 Gbit/s	1 to N
IEEE802.3ba 100GBASE-LR/ER	25.78125 Gbit/s	4
32G Fiber Channel	28.05 Gbit/s	1
Infiniband 26G-IB-EDR	25.78125 Gbit/s	1 to N

Table 1. *20+ Gbit/s High Speed Standards.*

When using Vector Network Analyzers (VNAs) to evaluate backplane and interconnects, one of the most basic considerations is the frequency range over which to make S-parameter measurements. The choice of frequency range affects the ability to locate defects, the correlation between simulations and measurements, and ultimately the ability to make good decisions concerning cost/performance trade-offs.

This white paper discusses the importance of both high and low frequency test limits and also their impact on your time domain results.

High-Speed Harmonics Increase Required Frequency Range

It will come as no surprise that as bit rates increase, then the upper frequency limit for evaluating backplane and interconnect transmission characteristics must also increase. Higher speeds basically translate into higher test frequencies being required to perform measurements to the 3rd or 5th harmonic of the NRZ clock frequency. For example, for a 28 Gbps data rate, this means either 42 GHz or 70 GHz stop frequency for an S-parameter sweep. Figure 1 shows a spectrum of a 14 GHz square wave which would be the clock frequency for a 28 Gbps NRZ signal. This example shows the spectrum after the signal has been passed through a connector/cable assembly. Attenuating the harmonics of the clock frequency will distort the signal and hence the need to characterize the frequency response of transmission media to higher frequencies – ideally to at least the 5th harmonic.

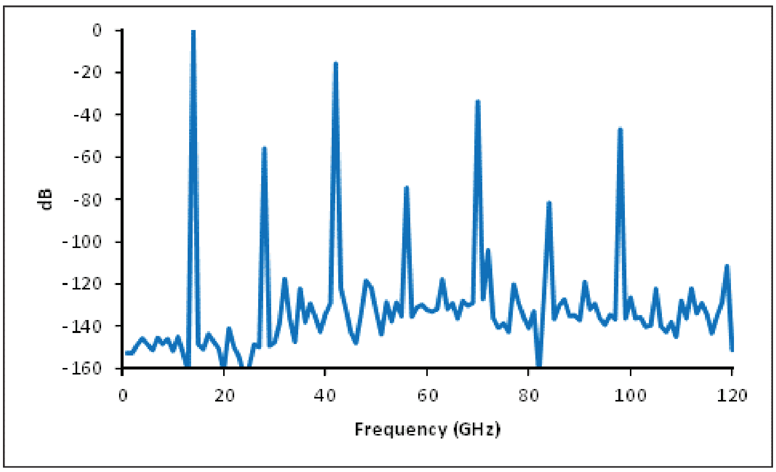

Figure 1. *Harmonic Content of 28 Gbps NRZ Clock Signal.*

Upper Frequency Data Impact on Simulation Stability

There is another way to think about the requirement for the upper measurement frequency; that is from the viewpoint of causality. Causality is simply a statement that the output from an electrical network should occur after the stimulus. Lack of causality, where the output appears to occur prior to the stimulus, can be observed when poor S-parameter data is transformed into the time domain for use in circuit or other simulations. Non-causal S-parameter data can be the cause of unstable simulations which may not converge to a solution or may lead to inaccurate results.

One cause of poor S-parameter data is insufficient higher frequency data. For ideal causality, S-parameter data would be available from DC to infinity – not a very practical situation, at least for the upper limit. Figure 2 shows the time domain representation computed from S-parameter datasets with upper frequency limits of 40 GHz and 110 GHz. As can be seen, the negative-time (non-causal) energy is much greater for the 40 GHz situation. The vertical scale is small in Figure 2 but even this level of energy can matter in many simulations.

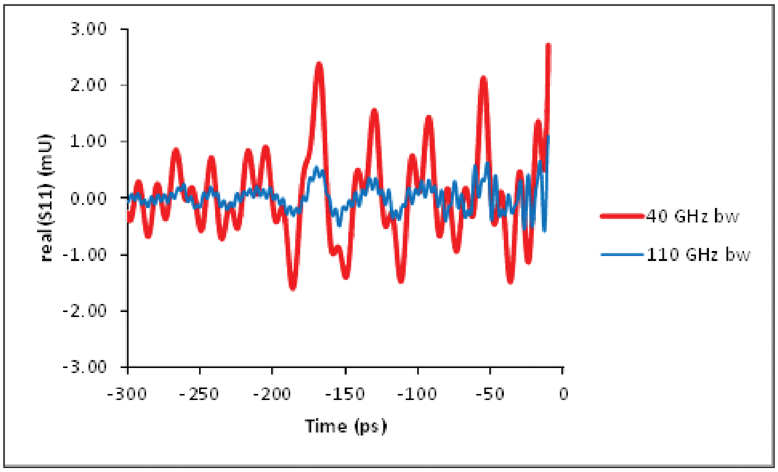

Figure 2. *Non-Causal Results for Various Data-Set Bandwidths*

In theory, massaging the frequency domain data can reduce these problems; however this can lead to potential issues related to distorting the actual physical behavior of the device. It is therefore often safer and more accurate to use as wide a frequency range as possible up to the point where repeatability and related distortions obscure the results (e.g., the DUT starts radiating efficiently making the measurement very dependent on the surroundings). The desire for wider frequency range data becomes more compelling as faster and more complex transients are being studied in the higher level simulations.

Near-DC Measurements – No Less Important

Once the upper frequency need has been addressed, it is time to look at the other end of the spectrum. It is important to remember that accurate measurements to the lowest possible frequency are still very important for signal integrity applications.

Often times the accuracy of your models can be improved by measuring down to as close to DC as possible. For example, consider the case where the measured S-parameter data for a backplane is fed into a software model in order to estimate the impact of that backplane on the eye pattern. Figure 3 shows what the eye pattern estimate will look like where the low frequency data has some error. In this example, it was found that a 0.5 dB error injected at a lower frequency (<10 MHz) on transmission could take an 85% open eye to a fully closed eye. Since mid-band (10 GHz) transmission uncertainty may be near 0.1 dB depending on setup and calibration – and higher at low frequencies – this eye distortion effect cannot be neglected.

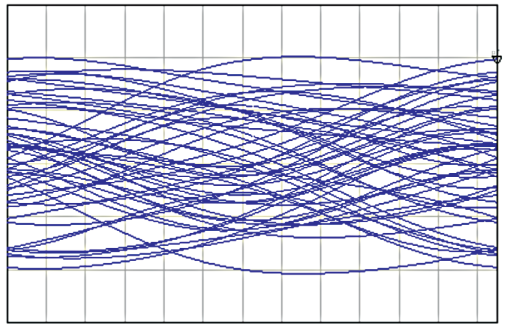

Figure 3. *With 0.5 dB insertion loss error at 10 MHz the eye pattern appears to be closed .*

Figure 4 shows how the resulting eye pattern will look if the low frequency measurement data is of good quality and extends down to 70 kHz. This prediction correlates very well with the actual eye pattern measured using an oscilloscope as shown in Figure 5.

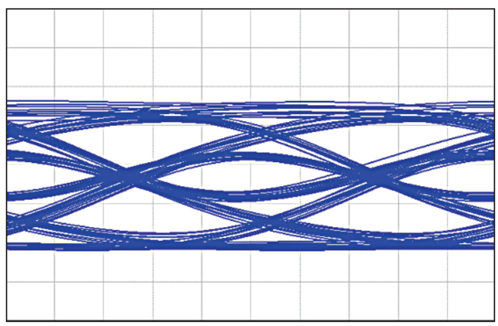

Figure 4. *Accurate S-parameter data down to 70 kHz reveals an 85% open eye pattern.*

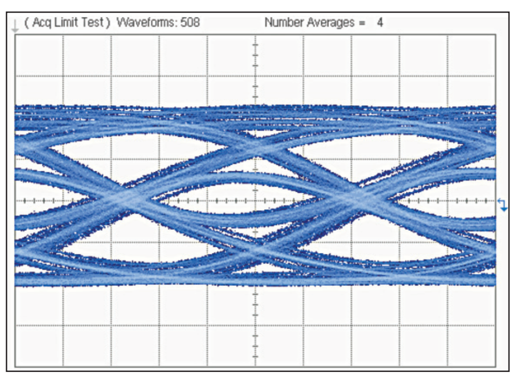

Figure 5. *Measured eye pattern on an oscilloscope verifies the accurate S-parameter result.*

Since the non-transitioning parts of the eye-diagram are inherently composed of low frequency behavior, the sensitivity of the calculation to the low frequency S-parameter data makes sense. Since the low frequency insertion losses tend to be small, a large fixed-dB error (which is how VNA uncertainties tend to behave) can be particularly damaging.

Time Domain – it's a question of both upper and lower frequency data

Passive components, as well as near-end and far-end points between daughter boards, must be measured in the frequency and time domains to assure that the transmission characteristics at each measurement point meet the standards. Using the best resolution capability improves your ability to locate discontinuities, impedance changes, and crosstalk issues.

The time domain performance of a VNA is critical when trying to locate defects. In general, the wider the frequency-sweep, the better is the time and hence spatial resolution. Figure 6 clearly shows the benefits of using S-parameter data captured over a wide frequency bandwidth.

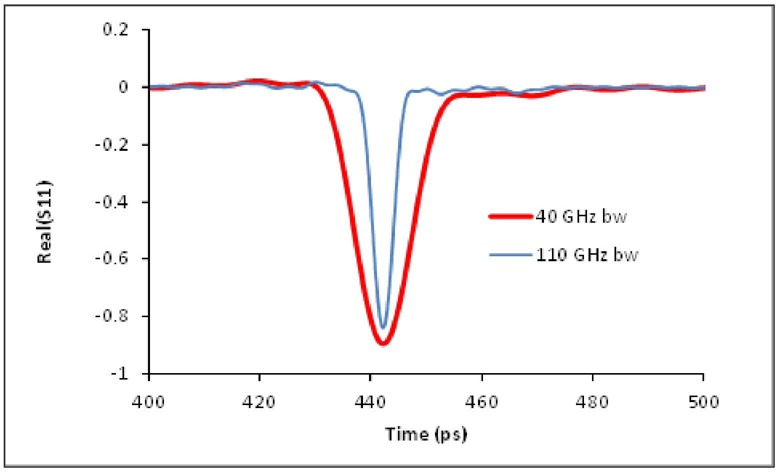

Figure 6. *The time domain resolution benefits of wider frequency bandwidths are clearly shown in these measurements of a short at the end of a fixture arm based on 40 GHz and 110 GHz data.*

Lack of good low frequency S-parameter data can also lead to further complications when converting into the time domain either for measurement of impedance changes along a line or for modeling. Resolution is maximized when Low-Pass time domain mode is used. This mode also permits characterization of impedance changes on the backplane. Low-Pass mode requires a quasi-harmonically related set of frequencies that start at the lowest frequency possible. A DC term is extrapolated that provides a phase reference, so the true nature of a discontinuity can be evaluated. Hence, the lower the start frequency is, the better the extrapolation of the DC term.

Figure 7 shows how the DC extrapolation of data can vary significantly depending on the lower frequency measurement cut-off point. In this case, extrapolation of measurement results from an analyzer with a minimum start frequency of f_1 would predict a value for the DC term, whereas a set of results that more closely approaches zero Hz (f_2) would provide a better DC extrapolation.

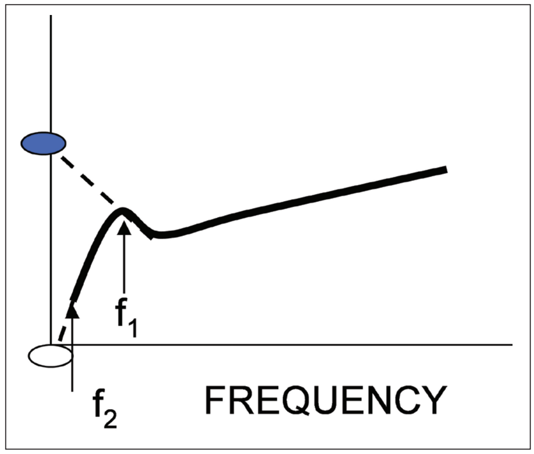

Figure 7. *DC Extrapolation from measured S-parameter data.*

A poorly estimated DC term then leads to an erroneous view of a device under test. Figure 8 shows the situation for a step change in reflection coefficient. Prior to 200 ps, the impedance of the line was 50 ohm and after that zero ohms. With a bad DC extrapolation, the 50 ohm section can clearly be seen to show sloping impedance along its length, whereas with a good extrapolation, the 50 ohm line is seen correctly.

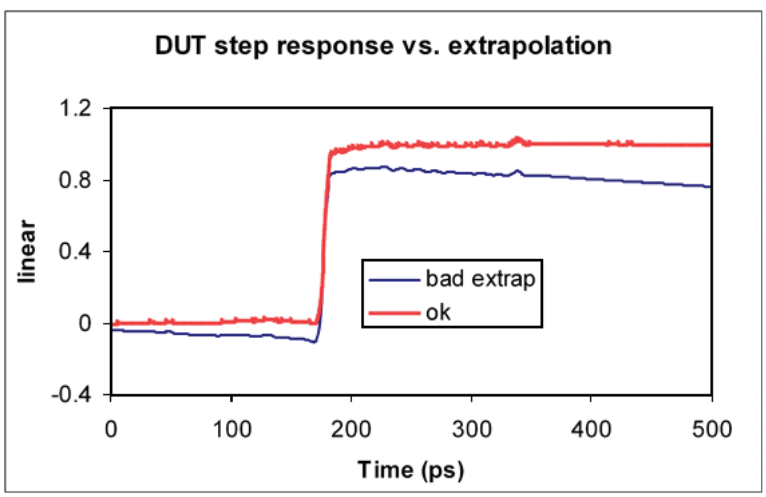

Figure 8. *Impact of poor DC extrapolation on time domain results.*

Getting the Best of Both Worlds

From the foregoing it can be seen that the ideal VNA would have as a low a start frequency as possible and a stop frequency as high as required based on the bit rate and causality concerns. A VNA depends on directional devices to sample forward and reverse direction signals in order to make the various ratio measurements to compute the S-parameters. Typically microwave couplers are used. However, the coupling performance of these devices unfortunately degrades at lower frequencies, below say 1 GHz, which reduces the dynamic range and the uncertainty of lower frequency measurements. A bridge allows one to go much lower in frequency without performance degradation since it does not rely on pure geometrical length (in wavelengths) to accomplish the coupling. Rather, the bridge uses lumped impedance sources at low frequencies and distributed ones at higher frequencies to accomplish the coupling. Analyzers are available that use a hybrid approach: coupler based architectures for the higher frequencies, and bridge based coupling devices at the lower frequencies.

Conclusion

As data rates increase, signal integrity engineers require ever widening frequency ranges and test equipment that maintains the accuracy they are used to. Vector Network Analyzers play a key role in helping them meet these challenges so they can make appropriate cost/performance trade-offs. When selecting a VNA, the users should be looking to maximize both their upper and lower frequency limits.

Anritsu

• United States
Anritsu Company
1155 East Collins Blvd., Suite 100, Richardson,
TX 75081, U.S.A.
Toll Free: 1-800-267-4878
Phone: +1-972-644-1777
Fax: +1-972-671-1877

• Canada
Anritsu Electronics Ltd.
700 Silver Seven Road, Suite 120, Kanata,
Ontario K2V 1C3, Canada
Phone: +1-613-591-2003
Fax: +1-613-591-1006

• Brazil
Anritsu Eletrônica Ltda.
Praça Amadeu Amaral, 27 - 1 Andar
01327-010 - Bela Vista - São Paulo - SP - Brazil
Phone: +55-11-3283-2511
Fax: +55-11-3288-6940

• Mexico
Anritsu Company, S.A. de C.V.
Av. Ejército Nacional No. 579 Piso 9, Col. Granada
11520 México, D.F., México
Phone: +52-55-1101-2370
Fax: +52-55-5254-3147

• United Kingdom
Anritsu EMEA Ltd.
200 Capability Green, Luton, Bedfordshire, LU1 3LU, U.K.
Phone: +44-1582-433280
Fax: +44-1582-731303

• France
Anritsu S.A.
12 avenue du Québec, Bâtiment Iris 1- Silic 612,
91140 VILLEBON SUR YVETTE, France
Phone: +33-1-60-92-15-50
Fax: +33-1-64-46-10-65

• Germany
Anritsu GmbH
Nemetschek Haus, Konrad-Zuse-Platz 1
81829 München, Germany
Phone: +49-89-442308-0
Fax: +49-89-442308-55

• Italy
Anritsu S.r.l.
Via Elio Vittorini 129, 00144 Roma, Italy
Phone: +39-6-509-9711
Fax: +39-6-502-2425

• Sweden
Anritsu AB
Borgarfjordsgatan 13A, 164 40 KISTA, Sweden
Phone: +46-8-534-707-00
Fax: +46-8-534-707-30

• Finland
Anritsu AB
Teknobulevardi 3-5, FI-01530 VANTAA, Finland
Phone: +358-20-741-8100
Fax: +358-20-741-8111

• Denmark
Anritsu A/S (Service Assurance)
Anritsu AB (Test & Measurement)
Kay Fiskers Plads 9, 2300 Copenhagen S, Denmark
Phone: +45-7211-2200
Fax: +45-7211-2210

• Russia
Anritsu EMEA Ltd.
Representation Office in Russia
Tverskaya str. 16/2, bld. 1, 7th floor.
Russia, 125009, Moscow
Phone: +7-495-363-1694
Fax: +7-495-935-8962

• United Arab Emirates
Anritsu EMEA Ltd.
Dubai Liaison Office
P O Box 500413 - Dubai Internet City
Al Thuraya Building, Tower 1, Suite 701, 7th Floor
Dubai, United Arab Emirates
Phone: +971-4-3670352
Fax: +971-4-3688460

• India
Anritsu India Private Limited
2nd & 3rd Floor, #837/1, Binnamangla 1st Stage,
Indiranagar, 100ft Road, Bangalore - 560038, India
Phone: +91-80-4058-1300
Fax: +91-80-4058-1301

• Singapore
Anritsu Pte. Ltd.
60 Alexandra Terrace, #02-08, The Comtech (Lobby A)
Singapore 118502
Phone: +65-6282-2400
Fax: +65-6282-2533

• P.R. China (Shanghai)
Anritsu (China) Co., Ltd.
Room 2701-2705, Tower A,
New Caohejing International Business Center
No. 391 Gui Ping Road Shanghai, 200233, P.R. China
Phone: +86-21-6237-0898
Fax: +86-21-6237-0899

• P.R. China (Hong Kong)
Anritsu Company Ltd.
Unit 1006-7, 10/F., Greenfield Tower, Concordia Plaza,
No. 1 Science Museum Road, Tsim Sha Tsui East,
Kowloon, Hong Kong, P.R. China
Phone: +852-2301-4980
Fax: +852-2301-3545

• Japan
Anritsu Corporation
8-5, Tamura-cho, Atsugi-shi, Kanagawa, 243-0016 Japan
Phone: +81-46-296-1221
Fax: +81-46-296-1238

• Korea
Anritsu Corporation, Ltd.
502, 5FL H-Square N B/D, 681
Sampyeong-dong, Bundang-gu, Seongnam-si,
Gyeonggi-do, 463-400 Korea
Phone: +82-31-696-7750
Fax: +82-31-696-7751

• Australia
Anritsu Pty. Ltd.
Unit 21/270 Ferntree Gully Road, Notting Hill,
Victoria 3168, Australia
Phone: +61-3-9558-8177
Fax: +61-3-9558-8255

• Taiwan
Anritsu Company Inc.
7F, No. 316, Sec. 1, NeiHu Rd., Taipei 114, Taiwan
Phone: +886-2-8751-1816
Fax: +886-2-8751-1817

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