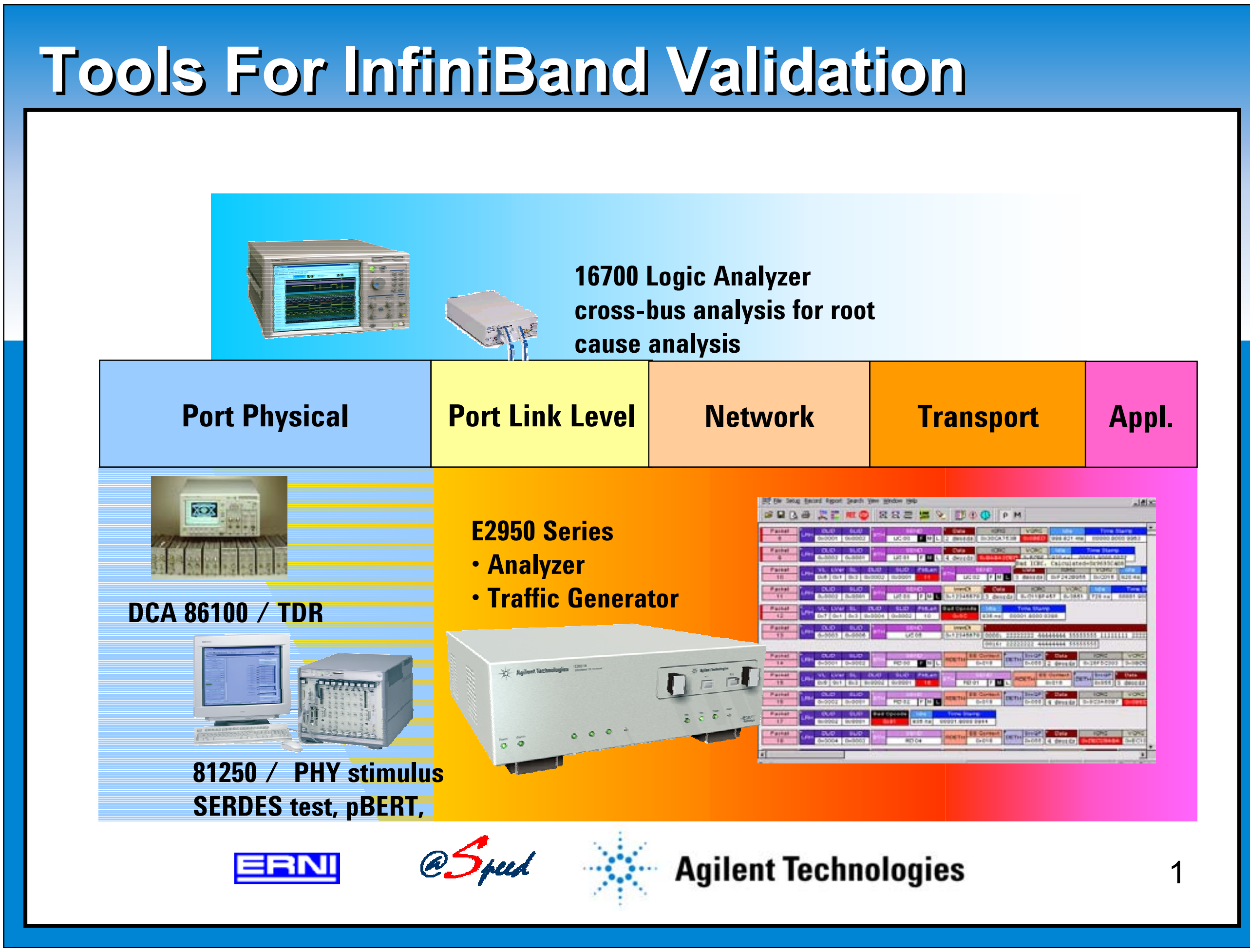

Tool Selection

These are examples of tools that can help you at various levels of the protocol; at the physical layer, TDR, scopes, Bit Error Rate testers, networking analyzers, spectrum analyzers provide insight.

The protocol analyzer works at the 10B and goes all the way up as high as possible.

Logic analyzers straddle the middle, they start working at 10B and then move up into the networking and transport layers. The strength of the logic analyzer is in the ability to perform cross bus analysis. As you move higher up you really want to transition into protocol analyzers as the tool of choice.

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atSpeed Technologies

Design Advances for the InfiniBand Architecture Physical Layer

August 1, 2001

Henri Merkelo, IEEE Fellow
Timothy Hochberg, atSpeed Technologies

Evolution of Signal Integrity

I.Traditional SI issues

- Achievement of signal quality by adherence to an impedance budget, to noise cancellation principles, to mode conversion avoidance and to design rules.

II. Advances in SI

- Introduction of active and/or passive devices for improving signals by conditioning them within the needed bounds when loss and dispersion are present.

Outline

- Traditional design concerns, issues
- **Dispersive loss becomes a challenge**
- **Manifestation of skew as timing, loss**
- **Management of signal conditioning**
- **Characterization of interconnections**
- Summary, conclusions, resources

Due to the significantly increased speeds that are migrating onto circuit boards and into cables, there is a new theme emerging among designers. It poses a number of design issues and problems but not without solutions. This presentation concentrates on the difficult subject of designing in an environment in which lossless assumptions can no longer be made and dispersion, which accompanies loss, needs to be taken into account accurately, lest amplitude, timing and jitter be completely misrepresented. It is shown that conditions of geometric complexity also are very demanding on the modeler and are frequently best measured rather than modeled. For these reasons, a methodology for measurement-based accurate design is reviewed together with discussions of such topics as manifestation and management of skew, provision of active or passive signal conditioning and optimization of equalization and signal conditioning.

Outline

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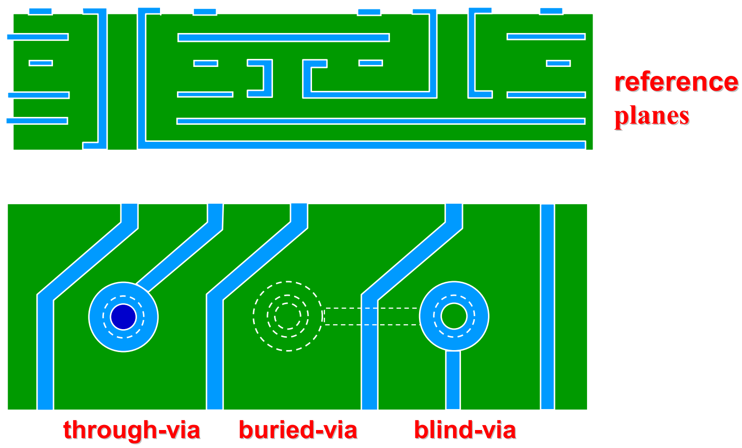
Traditional TDR/TDT

6

These frames symbolize the four main observations that can be made on a digital signal and illustrate the traditional applications of a time domain instrument equipped with a transmit/receive port such that it can show either the time domain reflection mode, TDR, or time domain transmission mode, TDT. The bottom two frames represent the many “faces” of cross talk and emphasize the fact that when contiguous signal lines are coupled, near end cross talk is never zero (except in the trivial case when the near end victim load is a short). In contrast, the far end can be manipulated to have nearly any value. The top right figure is a reminder that reflective effects can be dealt with, to a degree, by compensation techniques which require notions of localization and methods for estimation of impedance imbalance. Itcan be expressed as excess inductance when the impedance is too high or excess capacitance when the impedance is too low. Agilent instruments are equipped to give these values when the region of interest is designated by the user.

The first frame is purposely discussed last since it is frequently glossed over in most discussions; the propagated signal, in fact, carries a great deal of information, especially when the transmitter step generator produces a very short risetime signal, as it does in a TDR/TDT instrument. The causes for signal degradation in the transmission mode are numerous. It is shown that characterizing these causes accurately provides the means for a number of design options and solutions.

Vias in Multilayer Interconnections



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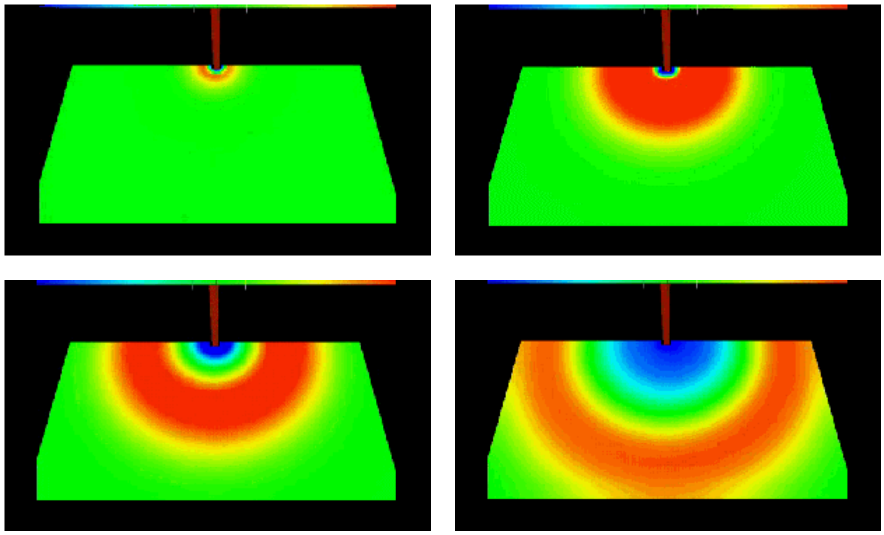
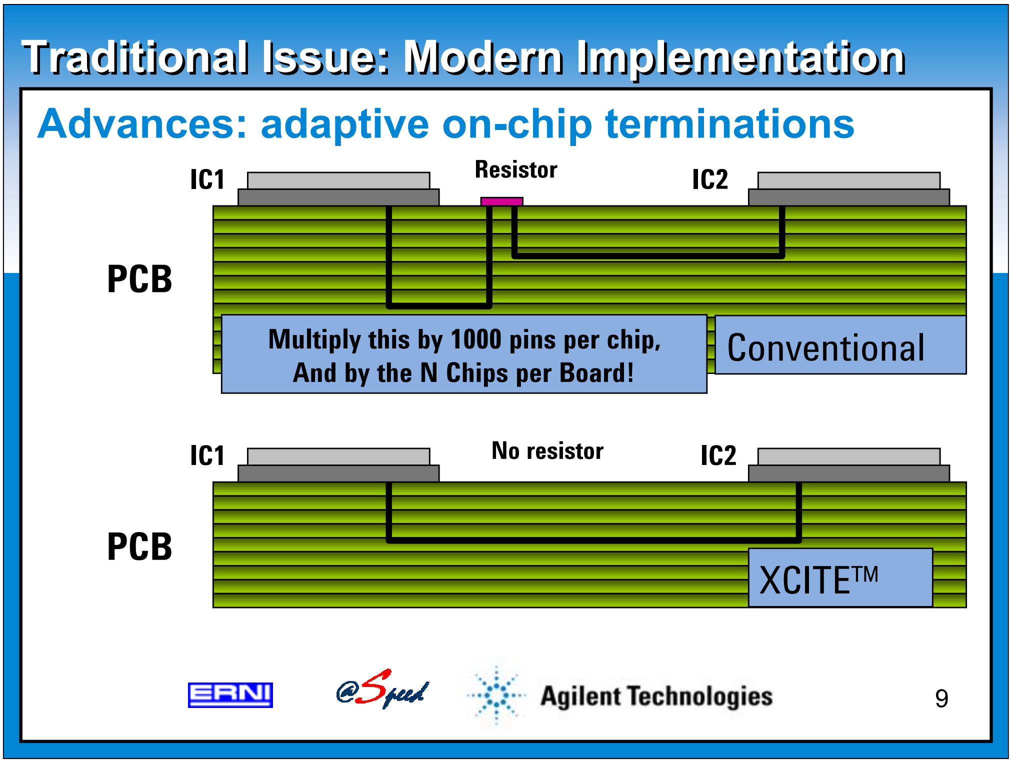
// Plane Waveguide Mode Conversion



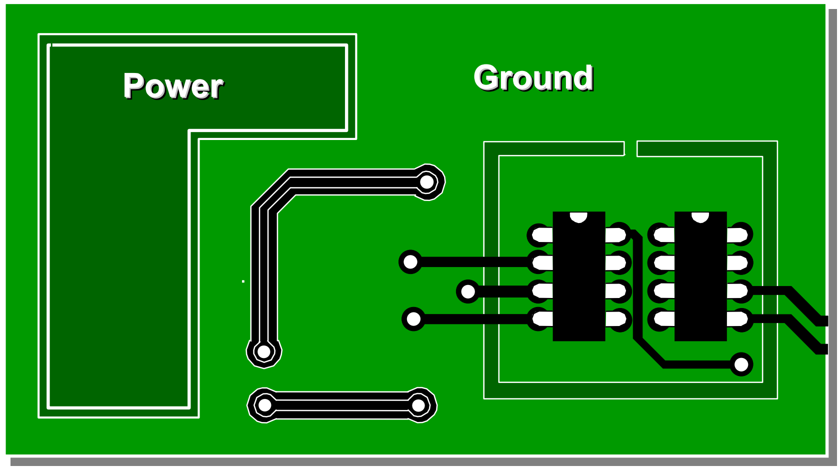


By focusing on the loss and dispersion issues, this presentation omits the mention of many well known signal integrity issues such as, for example, matched terminations. It's not that these concerns have diminished; in fact, just the opposite is true.

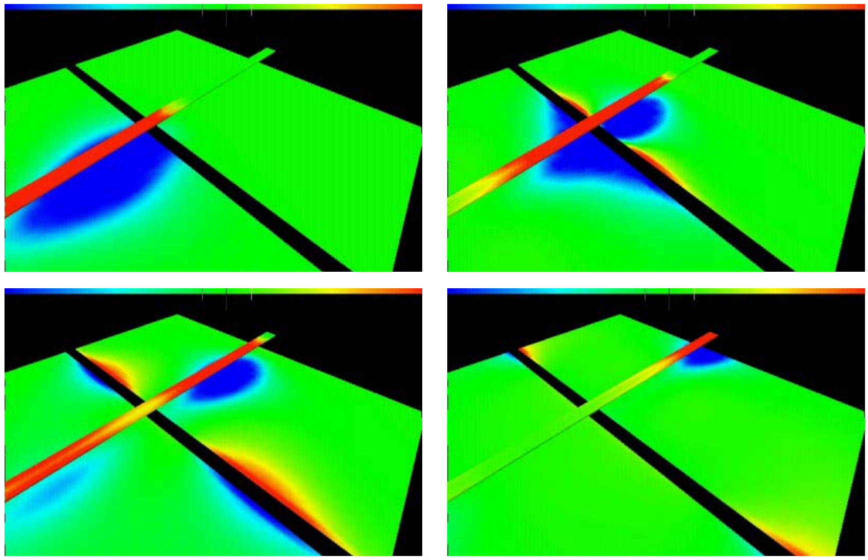
It is noteworthy, however, to mention the advances that are being made in accommodating the signal integrity needs in technology. The Xilinx chips, illustrated above, provide adaptive, on-chip terminations such as to eliminate the need to place resistors on circuit boards entirely.

By eliminating numerous vias, the signal integrity advantage is obvious. The cost saving is no less evident.

Examples of Split Reference Planes



Slotline Mode Conversion



Data Dependent Propagation Delay: Jitter

Real vs Effective

- Reflections from impedance discontinuities
- Simultaneous switching, ground bounce
- Invasive energy: mode conversion, emi, Xtlk
- Power supply noise, power bus reflections
- Effective dynamic capacitance on chip
- IC device threshold fluctuation, noise
- Dispersive loss, spectral content of data

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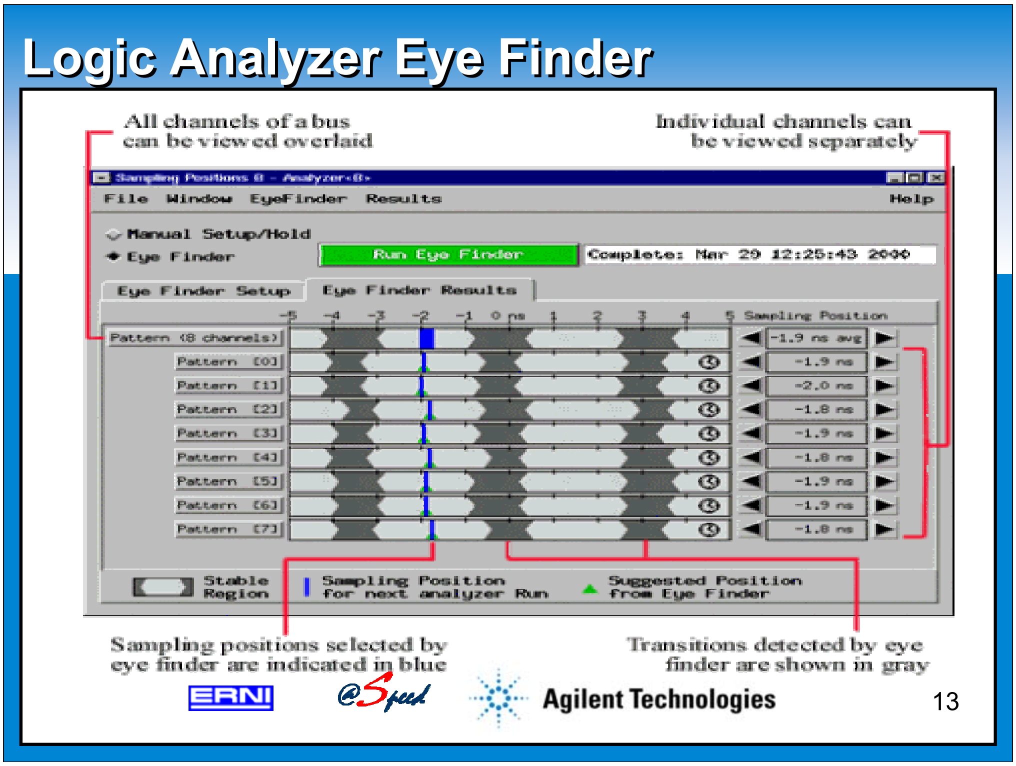
The purpose of deliberating in detail on the influence of dispersively lossy phenomena on signal integrity and timing stability is to demonstrate the effects of high speed in this environment on data integrity, particularly timing. This describes one class of data dependent signal integrity issues.

There are a number of other classes of data dependent phenomena that give rise to either real or apparent, data influenced, propagation delay variations.

Probably the best known is the simultaneous switching effect, variuosly known as delta I noise or ground bounce noise. It is a complex effect that occurs right on the onset of all signaling, directly on the chip. Its manifestation is on the risetimes of signals which become data dependent. Such a variation in risetime gives the appearance of data dependent propagation delay and, therefore, a data dependent jitter.

A number of other effects also contribute to timing integrity and can only be described in a setting within which time is less of a constraint than this forum.



The eye finder **examines the signals coming from the circuit under test and adjusts the logic analyzer's setup and hold window for optimal capture of high speed signals. Because eye finder uses the signals coming from the circuit under test, it yields the best results achievable. Eye finder uses the actual delay and latching circuits inside the logic analyzer, so it completely closes the loop on optimizing the adjustment of setup and hold. As discussed above, the ~ 100 ps resolution (and 10 ps in the 16760) with which the delays can be adjusted in Agilent's logic analyzer modules yields the highest confidence in accurate state measurements on high speed buses.**

Eye finder saves time. It takes less than a minute to run eye finder. No special setups are required. The user only needs to run eye finder once: when the logic analyzer is set up and connected to the target. Eye finder is totally independent of the skills and knowledge of the user.

The eye finder display **shows the regions of transition that are discovered on all channels and shows the sampling point selected by eye finder. If the user wants to select a different sample point on any individual channel, it can be done by just dragging and dropping the blue "sample" bar. Times in the eye finder display are referenced to the incoming clock transitions. The center of the display (labeled "0 ns") corresponds to the clock transitions.**

The New Theme

- There is a new momentum for significantly increased speeds; especially in serial transfer rates on backplanes and in cables.
- The manifestation of loss (and the concomitant dispersion) now influences many designs and designs to come.
- Accurate, broadband determination of differential characteristics provides the means for measurement-based design.

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Our industry has been particularly diligent in addressing standards and creating alliances that are willing to produce, define and enunciate architectures that hold the promise for increased high speed, full interoperability and the potential for providing means for substantially improving signal quality management when accompanied by good design.

These advances in charting standards and architectures create fertile conditions for leapfrogging current digital speeds in a number of settings. This presentation focuses on design issues associated with high speed signal properties when propagated through media that have dispersive loss and/or propagation characteristics dominated by complexities such that relying solely on modeling without the support of measurements becomes impractical. High speed is achieved by accurately simulating the propagation process through measured characteristics and by incorporating within the design process suitable signal conditioning. The signal conditioning can take one of several forms which are described and illustrated.

The New Terminology

- Spectral characteristics
- Loss, dispersion
- Signal conditioning: SC
- Active, passive SC
- SC optimization
- Equalization
- High-pass
- Preemphasis
- Preamplification

Signal Conditioning Compensation for Loss and Dispersion at High Speed

Outline

- Traditional design concerns, issues
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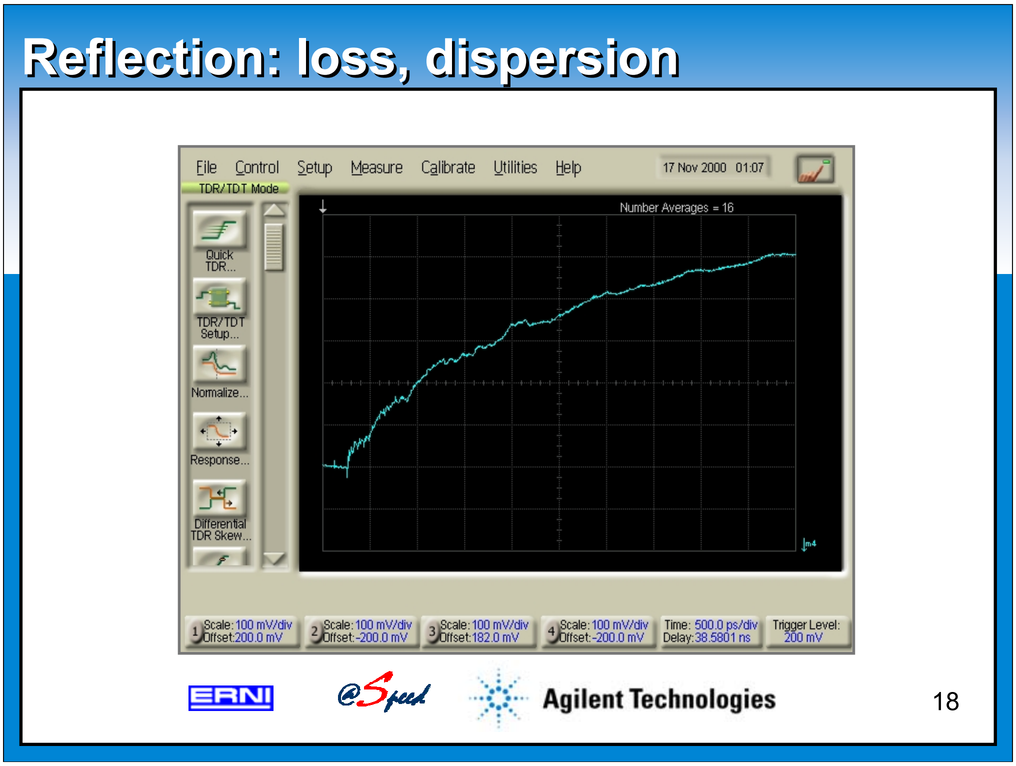
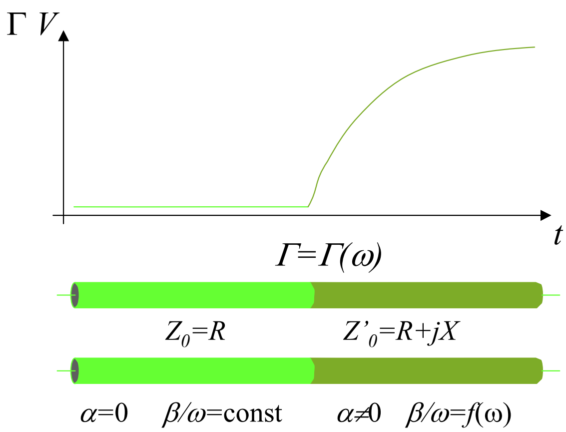
Due to the significantly increased speeds that are migrating onto circuit boards and into cables, there is a new theme emerging among designers. It poses a number of design issues and problems but not without solutions. This presentation concentrates on the difficult subject of designing in an environment in which lossless assumptions can no longer be made and dispersion, which accompanies loss, needs to be taken into account accurately, lest amplitude, timing and jitter be completely misrepresented. It is shown that conditions of geometric complexity also are very demanding on the modeler and are frequently best measured rather than modeled. For these reasons, a methodology for measurement-based accurate design is reviewed together with discussions of such topics as manifestation and management of skew, provision of active or passive signal conditioning and optimization of equalization and signal conditioning.



There is a long standing, classical effect that is frequently cited when students are introduced to practical applications of time domain reflectometry, TDR. **When two transmission lines of the** same impedance **are joined together, there may be an unusual reflection originating from the interface of the two lines, as shown in the above screen shot. The unusual character of this reflection is in the fact that it exists at all (since the two lines are of the same impedance) and in the fact that, regardless of how short the risetime of the incident pulse is, the reflection rises very slowly. That is, in the example shown above, the incident pulse has a risetime of approximately 35 ps (characteristic of Agilent TDR plugin #54754 in an Infinium DCA mainframe #86100A). The reflection, however, is photographed on a 500 ps/div scale and is seen still rising even after four nanoseconds. The personal experience of the author is that the explanations for this phenomenon, at best, frequently lack clarity and, at worst, lack correctness.**

Γ Manifestation of Loss, Dispersion

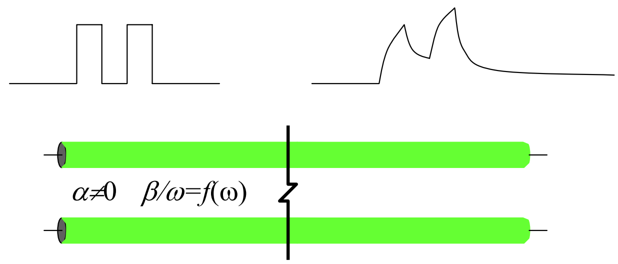


The insight and the explanation for the effect comes from the observation that the impedance of an ideally lossless line is a real number. In turn, the reflection coefficient is also a real number, since it is simply the ratio between the difference and the sum of the two impedances. When the two impedances are equal, the reflection coefficient is zero, an idealized case.

Clearly, when one cable has a different loss than the other, the reflection coefficient cannot be zero. What's more, the reflection coefficient is frequency dependent. A frequency dependence of the reflection coefficient is not easy to imagine but it is this frequency dependence of the reflection coefficient that gives this slow rise in the reflected signal. In effect, the interface becomes a filter for the reflected signal; by filtering the frequency content of the reflected pulse, the interface distorts the waveform of the pulse. The distortion is also affected by the fact that the relationship for the phase has a dispersive character.

The quantitative information that can be derived from this reflection is slim. However, the fact that such a reflection exists between a low loss test cable and a DUT becomes the first warning sign that the medium is lossy and that special precautions are needed for accurate design in the medium.

T Manifestation of Loss, Dispersion



There is nearly always dispersion associated with loss (but not always loss associated with dispersion).

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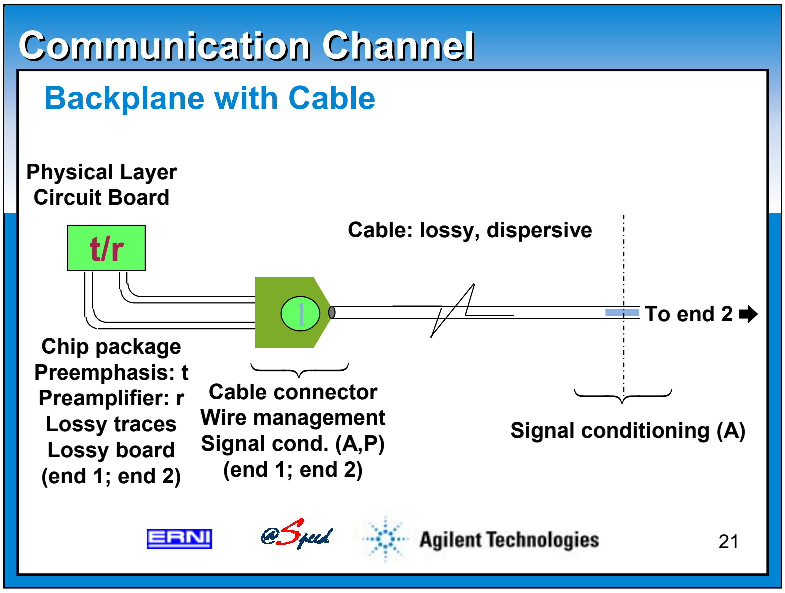
In typical systems, loss of signal propagating from transmitter to receiver has three root causes: conductor loss, dielectric loss and reflective loss. (Radiative loss is not considered in these discussions not because it is not important but because of the time limitations.) The secondary effect of loss is it's contribution to the net propagation delay. When the propagation constant is not linearly dependent on frequency, a path is said to be dispersive.

Conductor loss is due to the finite conductivity of metals. The conductivity of metals is generally frequency independent. However, because of the skin effect, conductor loss generally increases as the square root of frequency.

Dielectric loss is due to the absorption of electromagnetic energy in insulators such as FR4 or whatever material is in the circuit board. In our systems, dielectric loss increases more or less proportionately with frequency and starts dominating above one gigahertz.

Reflective loss, because it is due to geometric effects, can take on any frequency dependence and, as is illustrated later, can be full of surprises.

The combined effect of all the loss and dispersion mechanisms alters high frequencies the most and shows up, in the time domain, as a degradation of edge sharpness which causes the so-called intersymbol modulation, illustrated above. The effective propagation delay is data dependent and, as shown later, causes timing instability which, in turn, may cause synchronization problems.

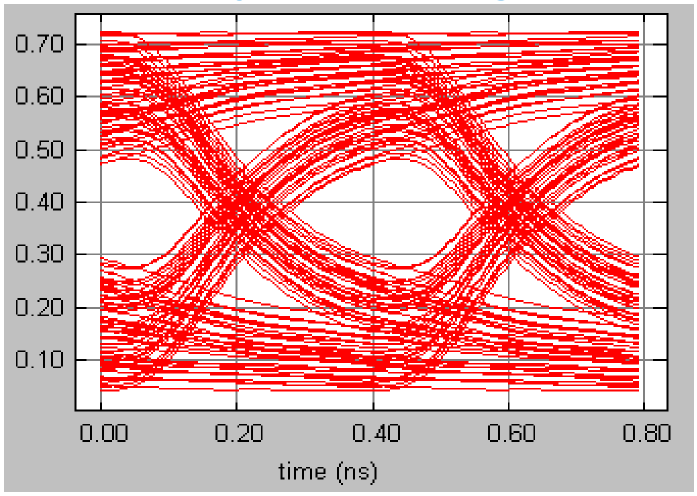


For purposes of focusing on the dispersive loss issues, a point-to-point communication channel is taken as a first design example. When the lengths of the circuit board traces and/or cabling associated with the communication channel are taken into account, dispersion and loss by themselves can affect signal quality to the point of system failure.

Interestingly, a number of very effective, active and passive, signal conditioning methods have been developed that can restore signals degraded by dispersive loss to a very high degree. For these techniques to work well, the predictive design process needs to be based on very accurate propagation characteristics. For these reasons, at high speed, a measurement-based design process is recommended and illustrated in a number of particulars that follow.

EPD Manifestation of Loss, Dispersion

EPD: eye pattern diagram

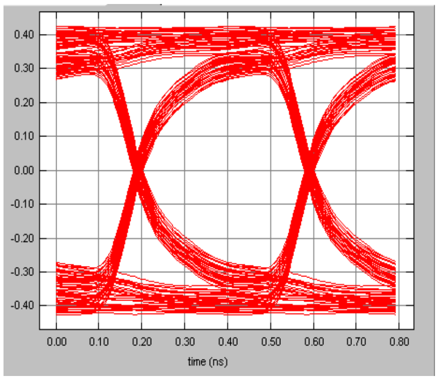
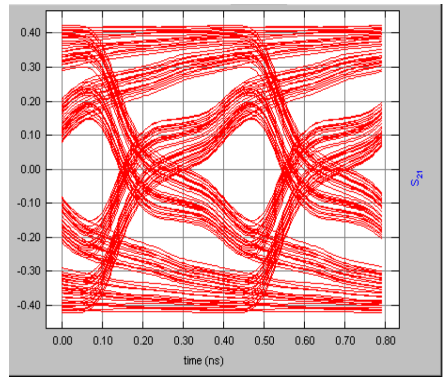


One of the most accepted standards for qualifying the performance of a design is to show the eye-pattern-diagram, EPD, that corresponds to a superposition of a substantial number of bits of a particular stream of data after this data has been propagated through the designed subsystem.

There are a number of issues that relate to the generation of the correct EPD that deal with the communication protocol itself. One of the main ones being that the test bit stream be statistically representative of the communication protocol and, at the same time, not be so overwhelming that the design becomes untestable. It is also important that the test is realistic with respect to the particular communication protocol, lest a lot of time is wasted in overdesigning the product.

The EPD can, of course, be generated in software and then validated with an instrument or simply generated directly on the built prototype with an instrument such as a high speed signal generator that includes a pseudo random bit stream, PRBS, function: Agilent #8133A. The instrument is capable of 3 Gb/s data sequences with risetimes of less than 100 ps.

Dispersion with Reflections

30 cm fr4	30 cm fr4 w/ 4cm hi Z
	
25 ps jitter	164 ps jitter

Data dependent jitter is greatly accentuated by reflections

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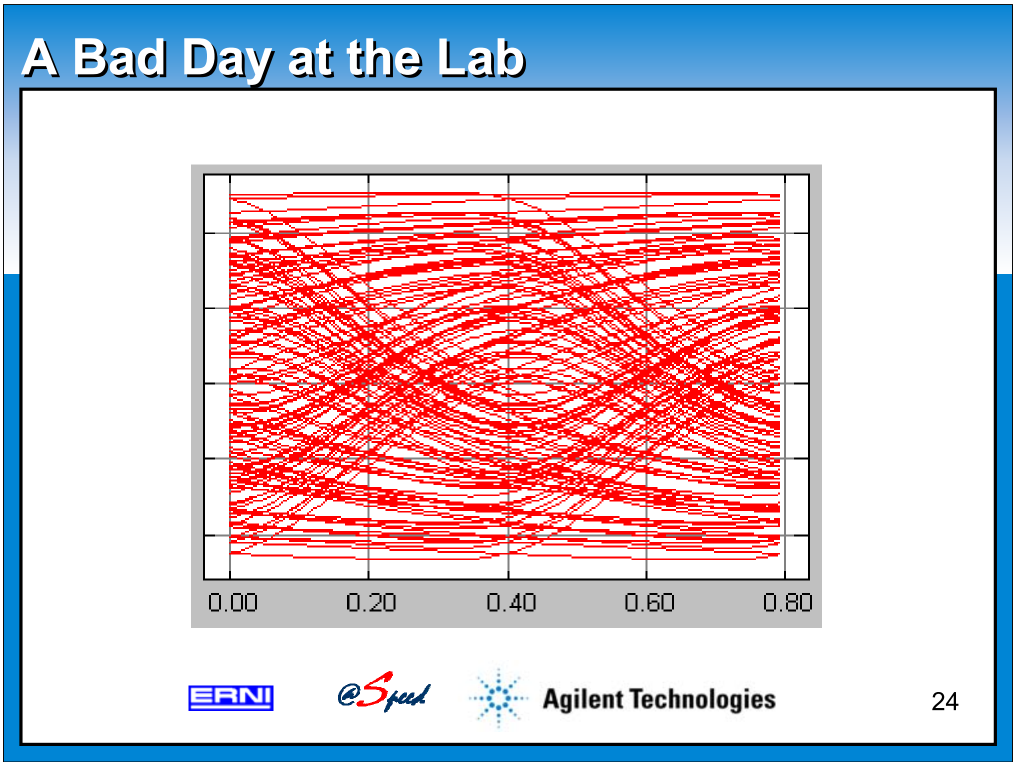


Neglecting to include correctly or accurately all of the physical effects in the design phase of a subsystem could result in a total failure of a prototype. Any one of the physical phenomena that attenuates signals unequally over the prevailing spectrum and randomizes the apparent propagation delay can be the root cause of such a failure. The more common situation is that a multiplicity of small effects, neglected in the approximations made in the modeling process, can grow to dominate the propagation characteristics. Unfortunately, the number of effects is not a short list and their inclusion is not always straightforward without good data.

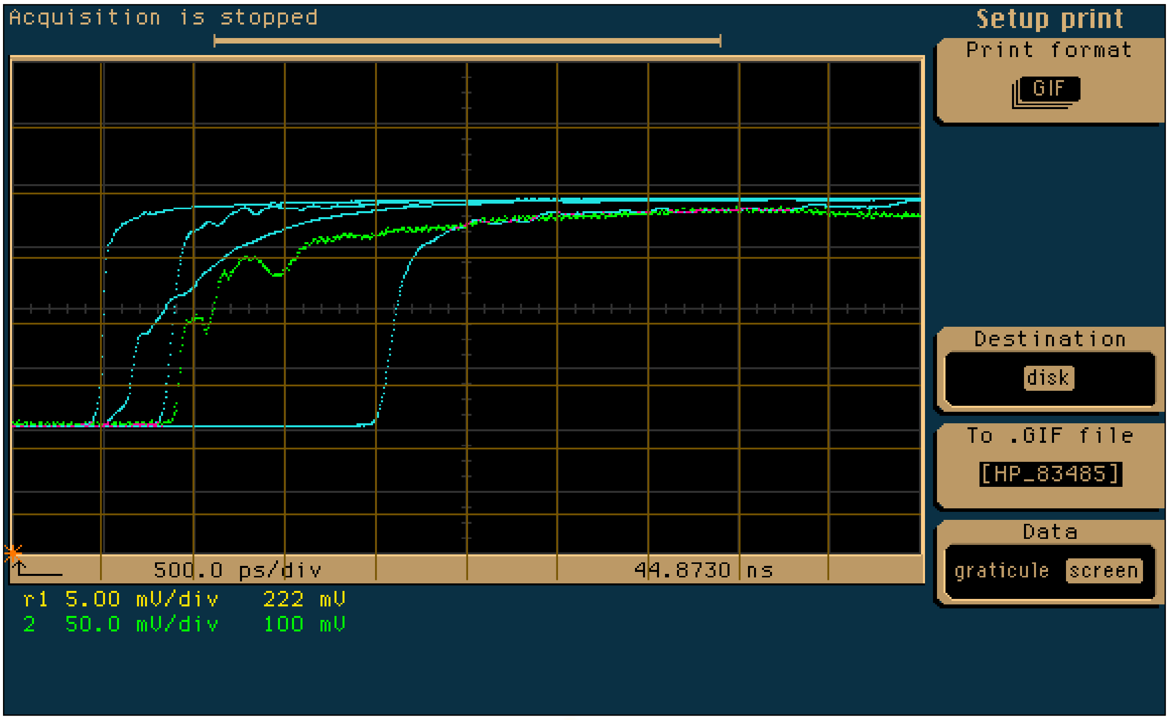
The eye-pattern-diagram shown above has been generated in software on the basis of measured characteristics. If it were to be generated with an instrument on a prototype, without a measurement-based design approach, such an instrument would be used for a tedious trial-and-error development. With a robust measurement-based design method, it's use would be merely for validation.

Even if the modeling of, for example, loss and dispersion are relatively correct within a continuum, it is shown in later examples that structural or geometric complexities can render the modeled parameters not even close approximations to the true characteristics. It is also shown later that several forms of signal conditioning are also powerful resources and, properly applied, can render a failing system into a functioning system with margin.

Measurement - Based Design

- Why?
- Where do I begin?

Signal Delay and Degradation



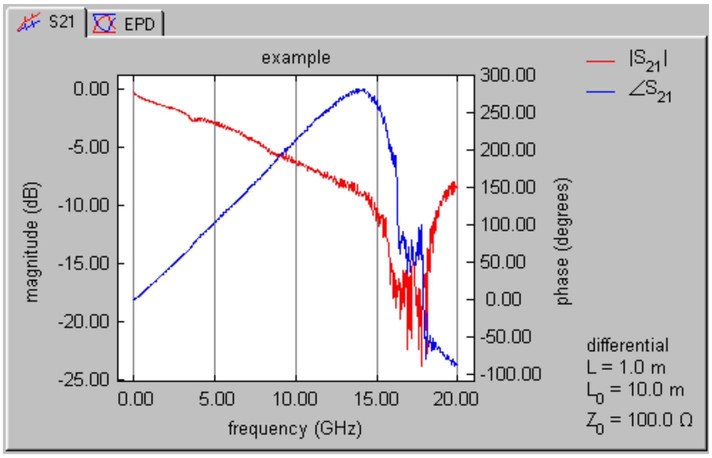
When a few practical conditions are met, short risetime signals carry broadband information in the transmission mode. Other than for qualitative observations, this resource has been largely neglected in the TDT applications.

Thus, every waveform shown above carries with it the signature of the medium and of the channel it propagates through. When this signal is mathematically compared in software to the signal launched at the transmitter end, the properties of the spectral characteristics of that channel are obtained uniquely. What's more, is that these characteristics are equally broadband for both single ended and differential applications.

The ability to extract broadband characteristics from time domain data adds substantial functionality to high speed time domain equipment in the TDT mode and takes further advantage of the intrinsic properties of high speed design. By mapping the high speed signature of the propagation channel onto the broadband spectral characteristics of the differential mode, the options for the designer are multiplied and the theme of measurement-based design is greatly enhanced.

Differential Dispersive Loss

TDT Method



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A number of topics need to be discussed when dispersive loss is to be considered.

Whereas there are no convenient analytical means for characterizing loss and dispersion in the time domain, the spectral properties can be both displayed graphically and analyzed quantitatively. Since any sinusoid can be described completely by its amplitude and phase, those two quantities are referred to as the vector properties of the characteristics.

The above data on the transmission properties of a cable have been obtained by recording the TDT waveforms on a TDR/TDT instrument. The time domain data is then post processed with Oculous software to obtain the principal characteristic of a channel. This characteristic represents the degree by which spectral components are attenuated and by how much they are phase shifted when they arrive at the receiving end. This same characteristic could have been obtained with a vector network analyzer, VNA, equipped with a special multiport switch such as the ATN 4000.

The special feature of this data is that it is for the differential mode of propagation. Whereas TDR instruments have been designed with a differential mode function for some time, it is only recently that a VNA could have a broadband switching module suitable for automated measurements in that mode of propagation.

Mixed Mode S-parameters

$$\begin{array}{c} \text{odd}\rightarrow\text{odd} \qquad\qquad \text{odd}\rightarrow\text{even} \\ S = \begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{bmatrix} \\ \text{even}\rightarrow\text{odd} \qquad\qquad \text{even}\rightarrow\text{even} \end{array}$$

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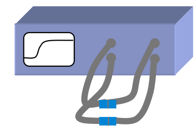
Mixed mode S-parameters are a way of describing the scattering of a four-port component that is designed to be used in the differential mode. A four port device that is used in the differential mode can be regarded as having two differential ports, each of which supports both the even and the odd mode signals. The structure of the mixed mode S-matrix mirrors the quantities of interest: transmission, reflection and even-odd mode coupling or conversion.

The S-matrix is divided into four quadrants. The upper left quadrant describes scattering of the odd mode into the odd mode. So, for instance, the S_{DD11} parameter describes the amount of odd mode signal reflected when the first differential port of the device is excited with an odd mode signal. It is this first quadrant that is of primary importance from a signal integrity point of view when operating in the differential mode. Similarly, the lower right quadrant describes the scattering of the even mode into the even mode. The upper right and lower left quadrants describe the scattering of the odd mode into the even mode and vice versa. These two quadrants may be of interest because the even mode is more likely to be coupled to the external environment. The S_{DC} components could potentially affect emissions, while the S_{CD} components could be related to coupling of noise from the environment into the differential mode.

Note: Due to an unfortunate and misleading dual use of the term common mode, it is avoided here by using the even mode designation.

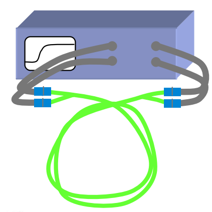
TDT Extraction of S_{21} with Oculus SW

- Fixture measurement [$m_{fix}(t)$]



- DUT and fixture measurement [$m_{DUT}(t)$]

- $S_{21}(\omega) = M_{DUT}(\omega)/M_{fix}(\omega)$



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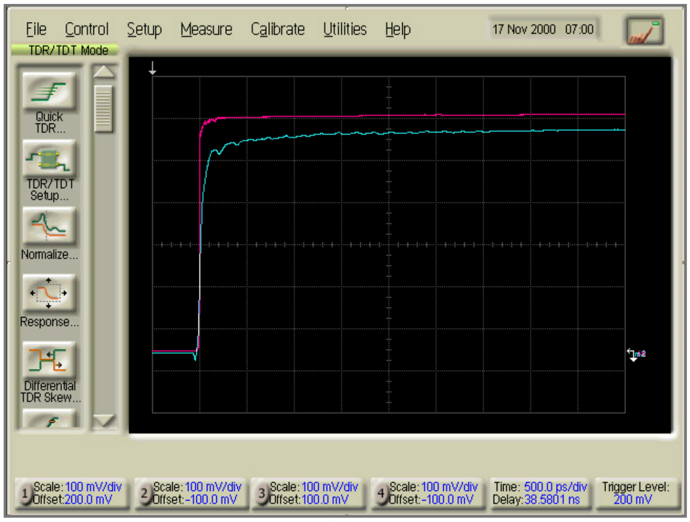
Transmission mode measurements have always been made on a TDR, largely for propagation delay measurements and for some overall attenuation estimation. By analyzing the propagation characteristics carefully in software, a much richer data set is obtained with which design can be carried out.

Also, because of the rarity of differential mode instrumentation, the TDT-to-spectral transmission characteristics extraction offers one more choice for obtaining differential data.

TDT Extraction Data



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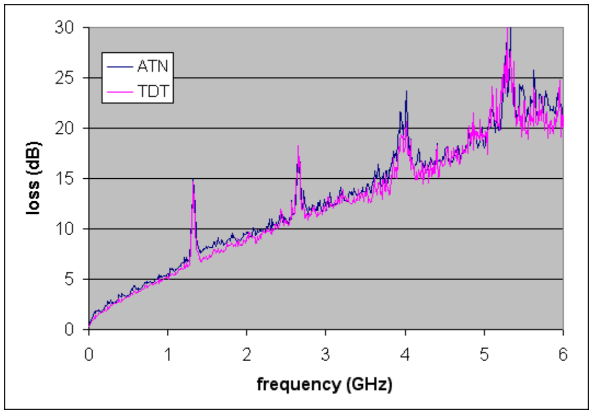
The spectral data shown earlier (in the slide titled Broadband Differential Dispersive Loss) is obtained from the TDT waveforms shown above. After some experience with fixturing, the above waveforms are acquired as easily as operating a laptop, since the TDR instrument is entirely based on a windows operating system. As mentioned earlier, the vector characteristics are obtained by post processing in Oculus which then provides means for scaling, cascading (assembling multiple characteristics) as well as signal conditioning either by equalization or preemphasis.

S-Parameter Extraction

Spectral Manifestation, Complexity



Spectral complexity within a cable

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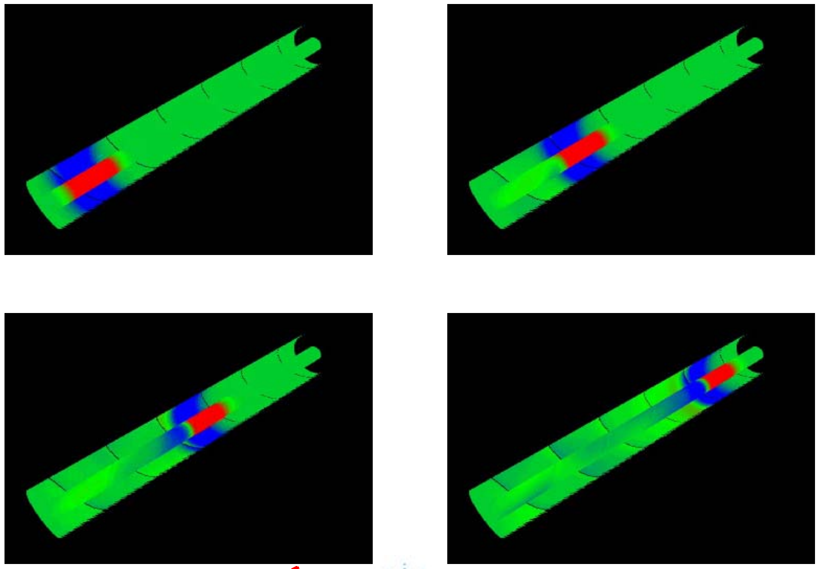
Effect of Helical Ground Gap



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TDT, Two Port VNA or Four Port?

Now the choice exists to fit need and budget:

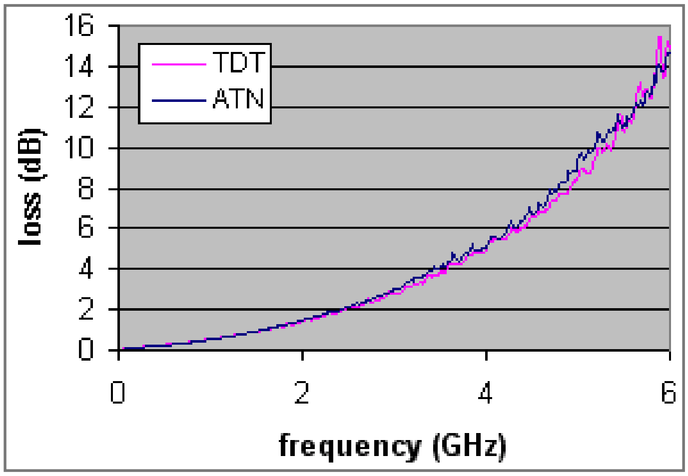
(TDR/TDT w/SW, VNA, 4pt-VNA)

- **Design in single ended vs. differential mode**
- **Desired bandwidth; desired sensitivity**
- **Comfort level with time vs. frequency domains**
- **Versatility of instrument for other uses**

The excellent developments in the past year now offer choices for quantitative characterization for differential mode designs. That, in itself, is a great development. The choices are based largely on needs, preferences and how those needs can be satisfied within budgetary constraints and with minimum effort.

There are advantages to being equipped with frequency domain instruments just as there are advantages to being equipped with high speed, broadband, time domain instruments. With fear of overstating the obvious, it won't be discussed that both is best and that upgrading is also an option. These differences and preferences can be discussed on a one-on-one basis such that realistic design needs are taken into account fully.

18” RG-158 (77 ps Skew)



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A number of comparative tests were conducted for validation purposes and reported at DesignCon 2001, Santa Clara, CA. Measurements were made of the S21 (transmission) parameters for a variety of samples. A typical result is shown which compares an ATN, VNA measurement to an S21 extracted from a TDT measurement. Measurements were carried out entirely independently and the results compared by superposition as shown above.

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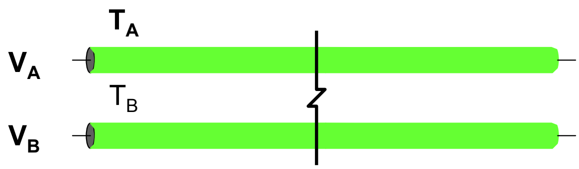
Definition of Differential Skew

$$\Delta t = |T_A - T_B|$$



Where T_A, T_B are single-ended propagation delays and V_A, V_B are single-ended voltages

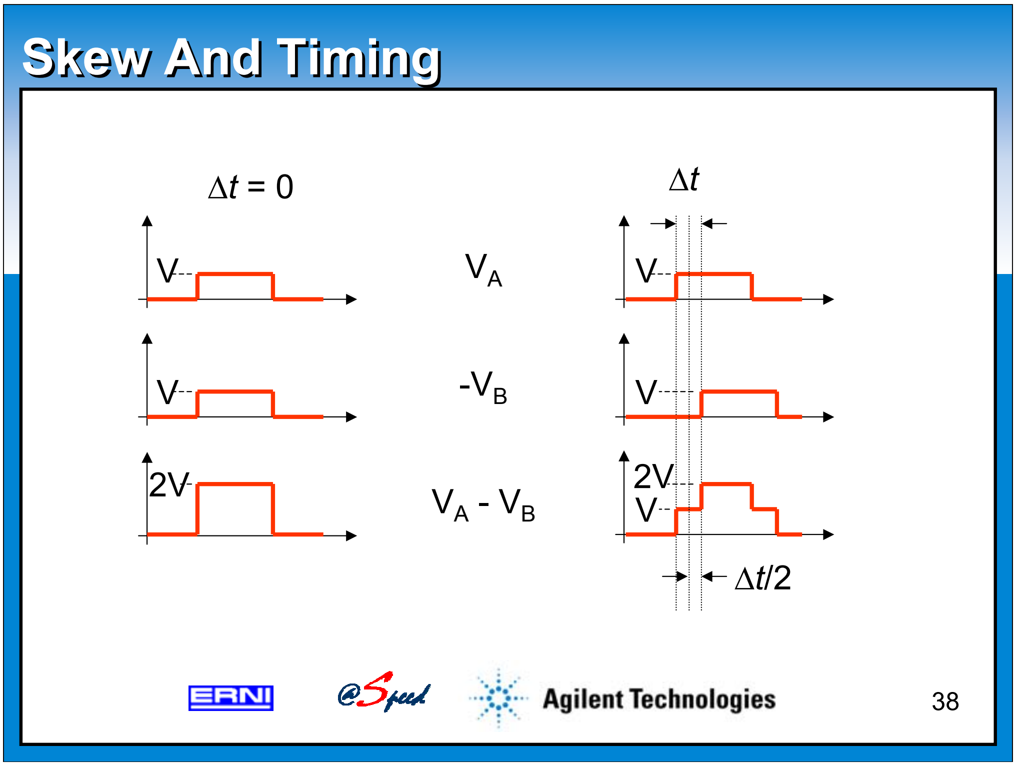
It is interesting that the definition of skew is straightforward but neither its implication on timing nor its effect on S21 are as plain.

Skew And Timing

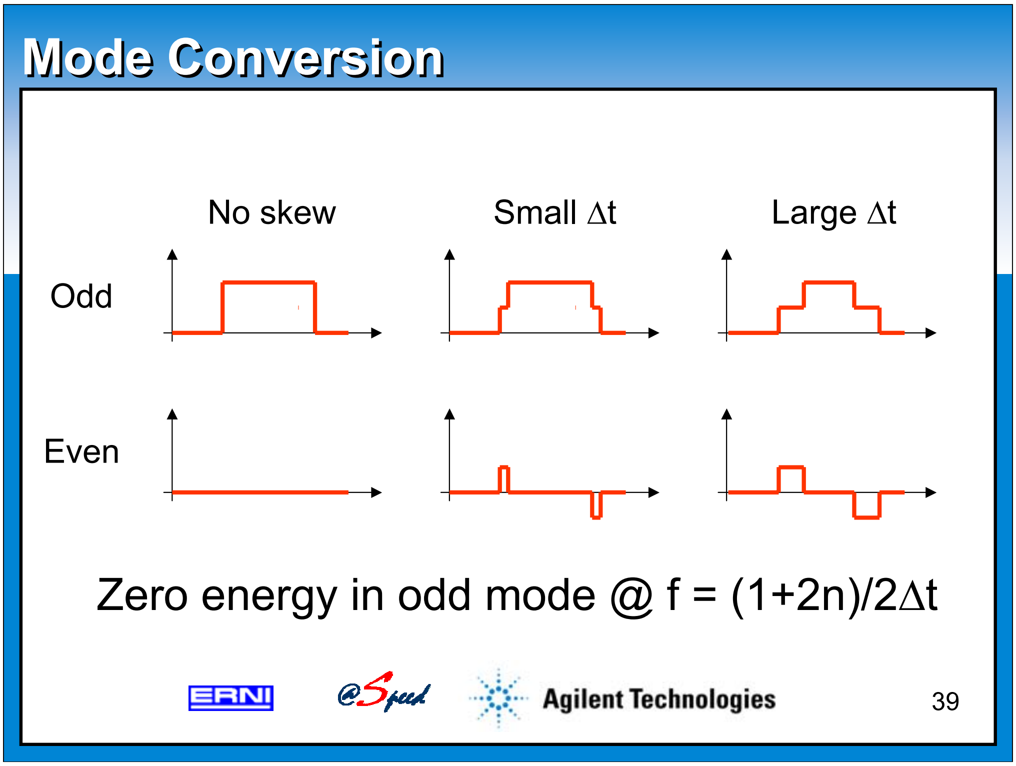
- Skew $\Delta t = T_B - T_A$
- $T_{diff} = (T_A + T_B) / 2 = T_A + \Delta t/2$

For a skew of Δt, the timing error is $\Delta t/2$

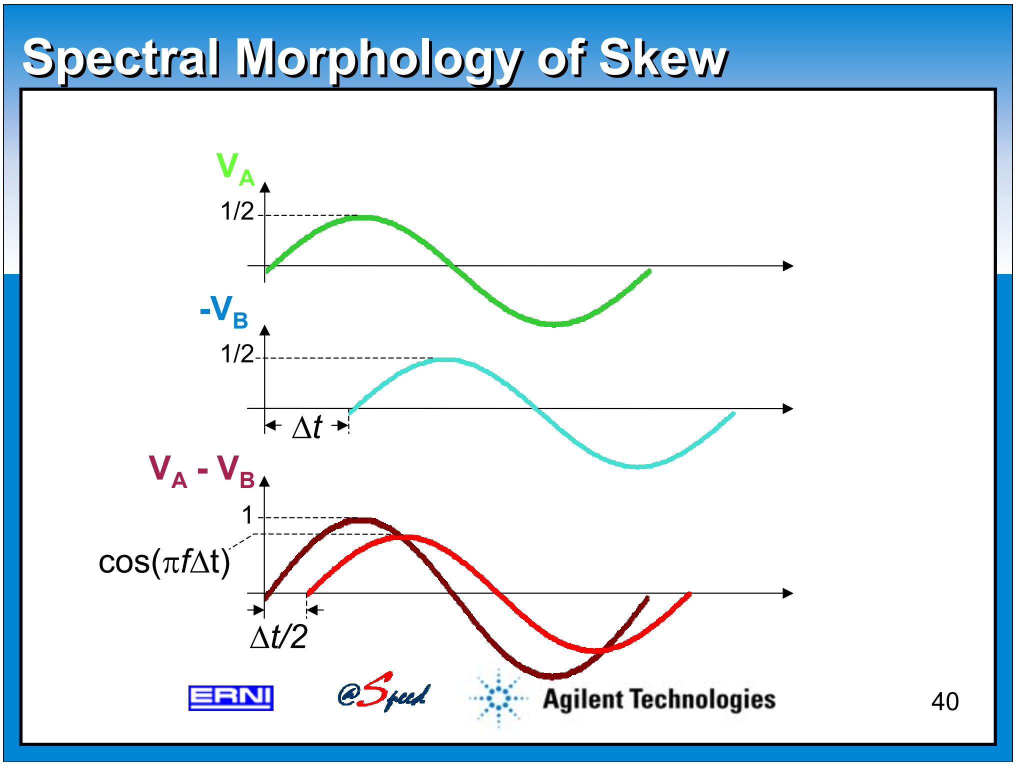
From a timing implication, skew in a differential signal context is only half as bad as what it seems to imply at face value. What is not obvious from a first inspection and what can be far more damaging is that it also influences the S21 transfer characteristic, which is review later.



It’s easy to see that when there is a Δt difference in propagation delay between the two halves of the differential pair, the mid point intercept is shifted only half that time when the risetimes are not zero.



It is easy to see that as the amount of skew increases, the area under the waveform of the differential (odd) mode progressively decreases. Since there is neither an absorption nor a reflection process to account for this decrease, the other modes are examined. For a purely differential signal, the magnitudes of signals on the two lines are equal and opposite in polarity; their sum is then zero. With skew, the signals do not superimpose exactly and create residual values when summed at all points in time. Skew, then, transforms some of the differential mode energy into even mode energy. This, of course, manifests itself in the frequency domain, as well.

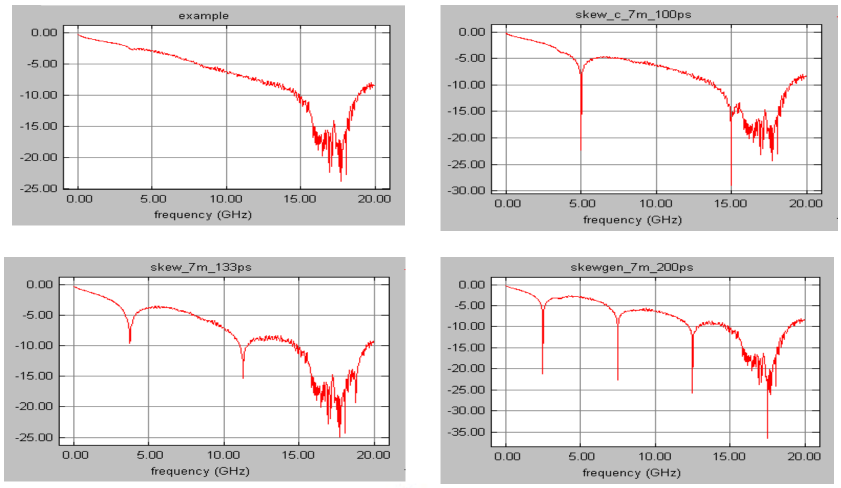


Just as in the time domain, each harmonic is delayed (skewed) by Δt and the resultant harmonic of the differential signal is delayed by half that much. The implication of a delay Δt between two sinusoids which are added has a different impact at low frequencies than at high frequencies. At low frequencies, the resultant differential amplitude is proportional to cos(π fΔ t), which progressively decreases as the frequency increases. Eventually, there is a frequency for which skew is exactly equal to half period. For that frequency, the resultant differential harmonic is exactly zero and, therefore, all differential mode energy at that frequency vanishes. That happens when πf Δt =π /2 or when f = 1/2 Δt or, more exactly, when f = (1 + 2n)/2 Δt, where n = 1, 2, 3 …..

Of course, since the amplitude of the differential signal reaching the receiver is diminished in the presence of skew, the component appears to have a corresponding loss which appears on the S21 characteristic. That's shown in the next frame.

Manifestation of Skew as Loss

$f = (1+2n)/2\Delta t$



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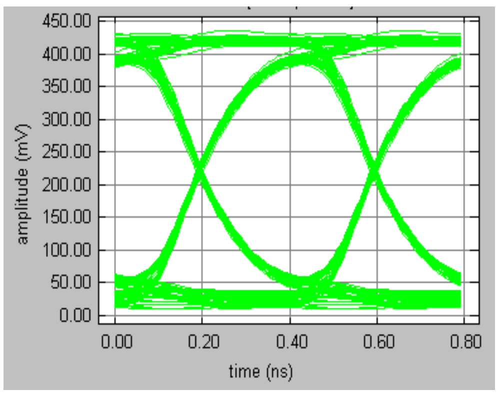
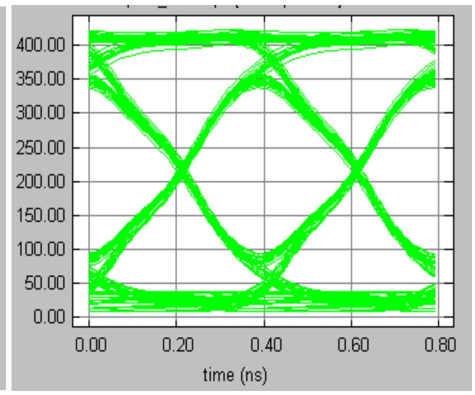
The S21 propagation characteristic shown earlier, as determined by the TDT method, is now captured with different set values of skew. Since the differential mode energy, in fact, vanishes at the frequencies indicated earlier, the sharp peaks on the characteristics shown above should go all the way to the bottom of each plot; it's only the graphical resolution that makes the peaks look finite. Note that the relationship for the frequency for which differential mode energy vanishes is verified for all such frequencies.

Manifestation of Skew

0 ps



200 ps



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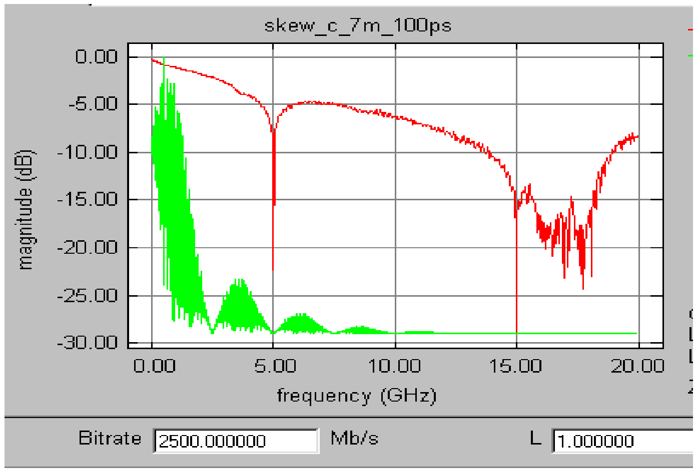
Now that it is clear that skew in the differential mode represents not only a shift in timing but also a loss of differential mode energy, it should not be surprising that it also exhibits itself in two ways in the eye pattern diagrams. The net shift in timing is not seen on the eye-pattern-diagrams since they are simply centered on the screen. The inflection in the waveform, however, is clear in the right hand figure and the loss of nearly 30% of magnitude is quite striking.

Design Rule for Skew?

Spectral Mapping



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To the author's knowledge, there is no well formulated design rule with regard to skew for differential mode signaling. Some criteria have been expressed in terms of signal risetime others have been simply arbitrarily set not to exceed so many picoseconds. Cables are frequently specified as so many picoseconds per foot. For a number of reasons, these approaches do not satisfy all conditions of propagation. For these same reasons, there may not be a single, satisfactory design rule for skew. When an understanding of the timing impact is added to the composite spectral propagation characteristic, however, some insight is gained toward developing a design rule. The result of that is that the design rule needs to be two rules or, at least, a two tiered rule.

Design Rule for Skew

Differential Signaling

- A two tier design consideration
- Timing: $\Delta t/2$ fixed vs statistical
- $\text{Cos}(\pi f \Delta t)$ additional damping
- Whichever more constraining

With this understanding of the impact of differential mode skew on system design, a priority list can be developed for implementing the most skew tolerant design. First of all, skew must be measured or estimated accurately. This can be satisfied with a high speed TDT instrument.

Fixed skew in differential signaling design is seldom an issue since, most of the time, it can be simply designed out. When skew is statistical, the system timing budget must be established. This provides an estimate of system tolerance to additional timing variability due to possible statistical variability of component performance.

With this preparation, the designer must be able to characterize the critical high speed nets that might be dispersively lossy. The determination (of S21) could be done again with the same high speed TDT instrument or a suitable VNA, as discussed earlier. A design tool (such as Oculous or any other suitable software) capable of merging S21 with various amounts of skew determines, for the designer, the influence of skew on eye closure for the critical nets. Thus, the design tool must be able to include, at the appropriate data rate, the effects of multiple S21's, perhaps of multiple skews, overall propagation lengths for each component and establish the most effective method for signal conditioning, as described in the next section: active (preemphasis, preamplification), passive (equalization). A final validation of a prototype can be carried out with a high speed signal generator, also as mentioned earlier.

Outline

- Traditional design concerns, issues
- Dispersive loss becomes a challenge
- Manifestation of skew as timing, loss
- **Management of signal conditioning**
- Characterization of interconnections
- Summary, conclusions, resources

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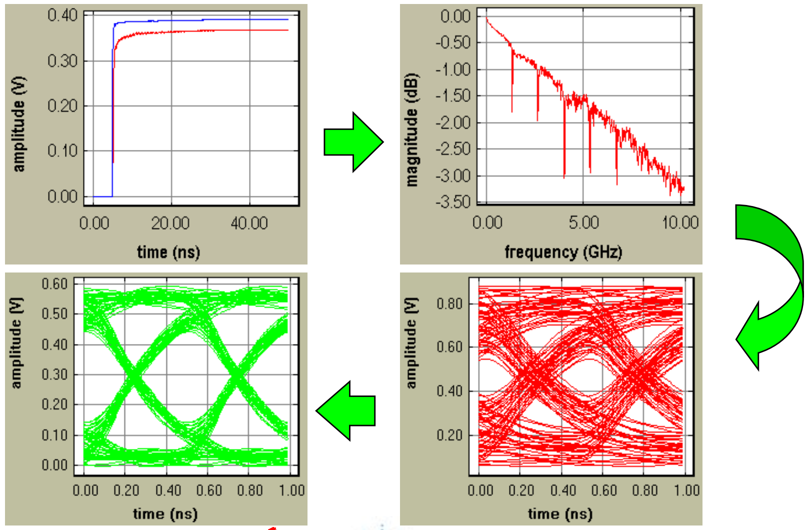
Due to the significantly increased speeds that are migrating onto circuit boards and into cables, there is a new theme emerging among designers. It poses a number of design issues and problems but not without solutions. This presentation concentrates on the difficult subject of designing in an environment in which lossless assumptions can no longer be made and dispersion, which accompanies loss, needs to be taken into account accurately, lest amplitude, timing and jitter be completely misrepresented. It is shown that conditions of geometric complexity also are very demanding on the modeler and are frequently best measured rather than modeled. For these reasons, a methodology for measurement-based accurate design is reviewed together with discussions of such topics as manifestation and management of skew, provision of active or passive signal conditioning and optimization of equalization and signal conditioning.

Measurement- Based Design

Single vs Multiple Components



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The steps followed in designing for performance when there is only one dispersively lossy component is different than when a number of components have loss, dispersion and other non uniform spectral characteristics.

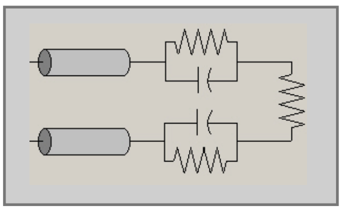
It is suggested that all designs begin with a measurement based determination of the spectral characteristic when it is expected to be complex. All other steps, other than prototype validation of design, take place in software.

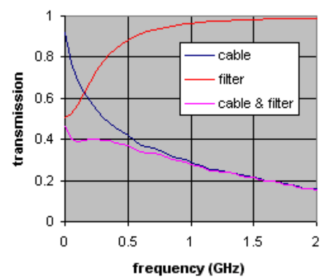
When only one component is the major dispersive element in the subsystem under consideration, determination (in Oculous or any other software) of the signal conditioning parameters is carried out immediately following the generation of the eye-pattern-diagram, EPD.

When multiple components are involved, such as microstrip traces, stripline traces, different dielectric circuit boards (circuit cards with fr4 but backplanes made of Rogers material), cables, different connectors, etc, the need for individual signal conditioning is neither necessary nor economical. The object is to obtain a composite spectral characteristic (such as in Oculus Matrix Cascade), generate the corresponding EPD and provide the signal conditioning of choice just once.

Equalization

- Use of a filter to flatten frequency response
- Simple RC (or CRC) filter is often sufficient
- Increases EPD opening, reduces jitter





Agilent Technologies

The most widely practiced signal conditioning for dispersive channels is a simple filter that restores, as much as possible, the balance between low frequencies and high frequencies that exist in the transmitted signal. Since all the cases of dispersively attenuating channels produce monotonic characteristics that favor low frequencies, a filter with a monotonic , high pass characteristic provides the restoration of the needed balance by favoring high frequencies. As simple of a concept as this is, it is remarkably effective.

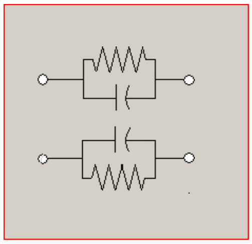
When needed, the equalization is implemented with a dc-blocking capacitor. More complex circuits have also been suggested. As illustrated in many examples throughout this presentation, the effectiveness and the low cost of the above choice seldom warrant additional complexity.

This form of signal conditioning requires only one set for any one transmit/receive net and can be placed anywhere in the net. The choice is frequently at the receiver end.

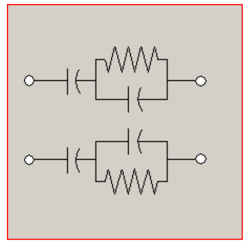
There is no closed form solution for the determination of the values of the components. This determination becomes complex when a number of paths in a single net have different spectral characteristics per unit length. This determination is best done in software equipped with an optimization engine.

Equalization in Oculus

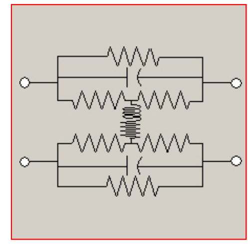
Differential Signaling



RC



CRC



LRC

The optimization routine in Oculus determines the values of all the components for best EPD.

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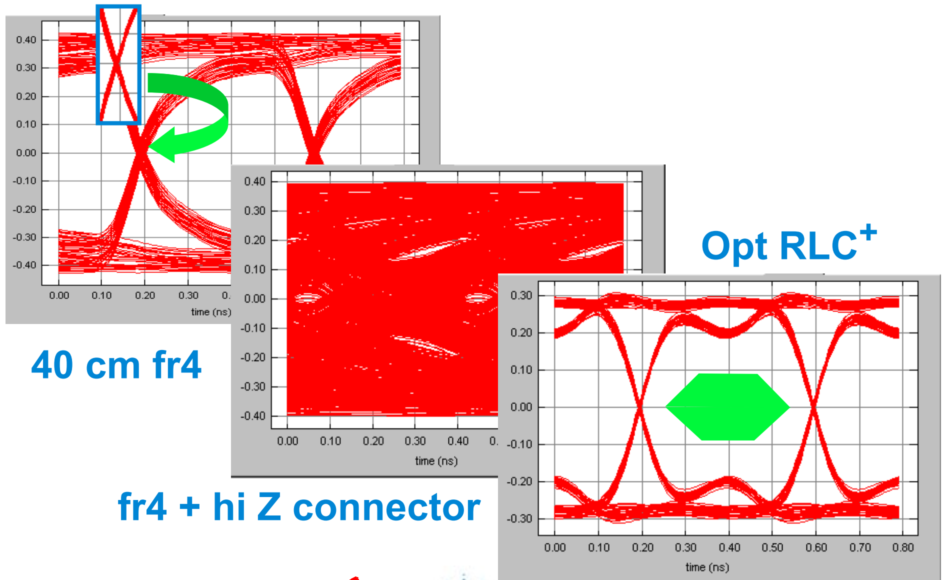
From a Bad day to a Beer day



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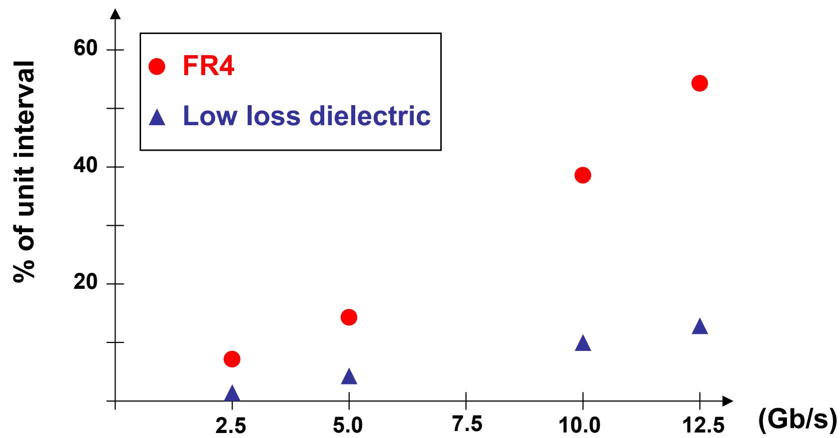
Jitter in ~30 cm of Trace



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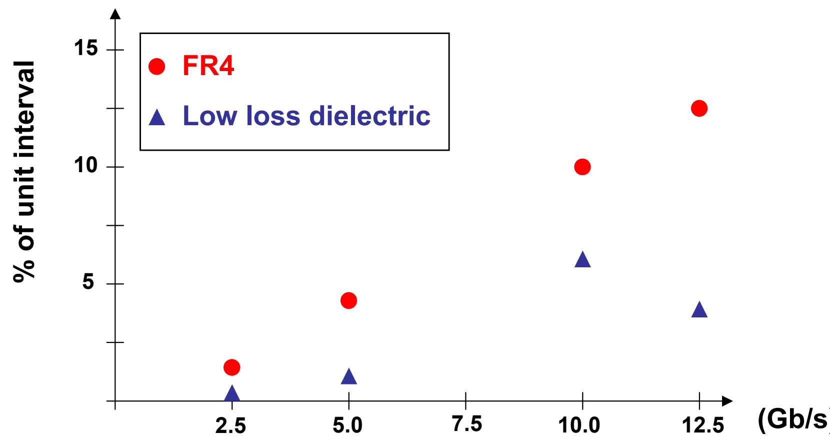
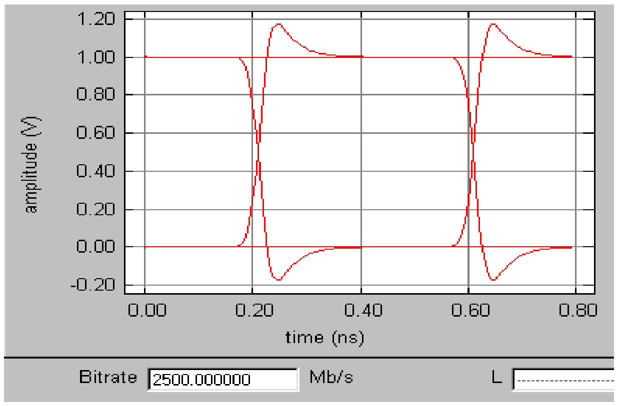
Jitter in ~30 cm of Trace w/ Equalization



Transmitter with Preemphasis



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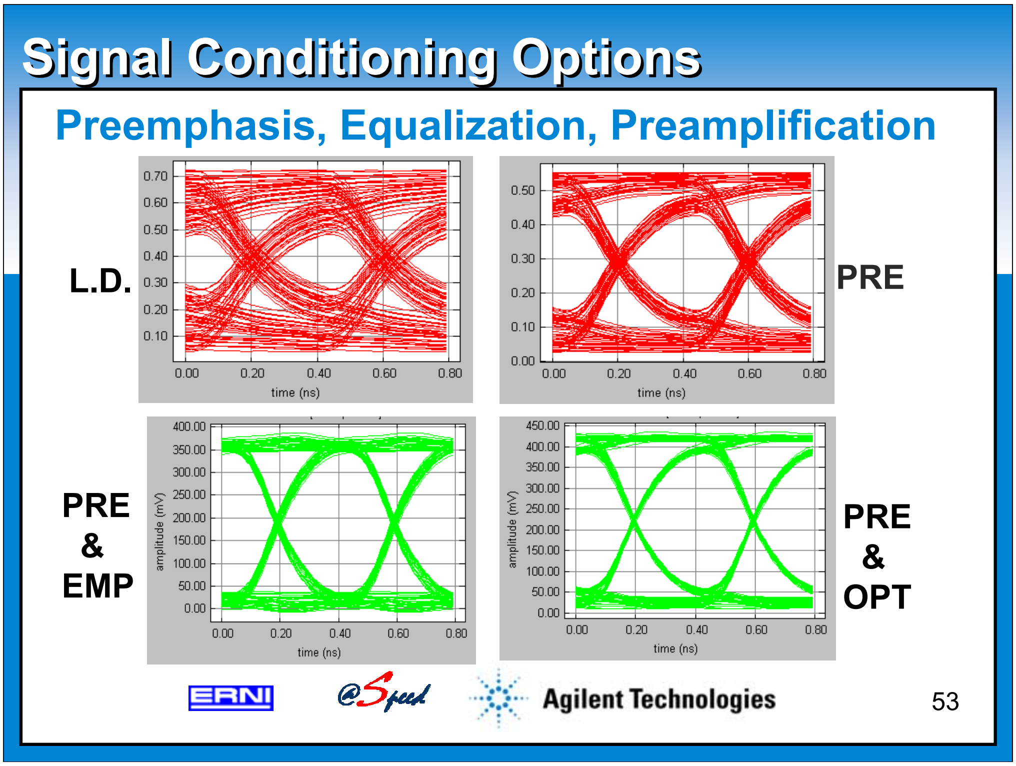
Preemphasis has a longstanding history in audio technology and can be thought of as being the converse of equalization. It consists of boosting the high frequency content in a signal in anticipation of the fact that the high frequencies are either preferentially attenuated or not registered well by the receiver.

There are a number of concepts for the implementation of preemphasis in the digital form. Its main implication to the IC designer is that it requires some form of waveform engineering in a digital environment. A number of manufacturers have announced transmitters in which preemphasis is implemented with varying degrees of sophistication. The characteristics and specifications are just becoming available.

The EPD waveform shown above has a mild form of preemphasis built into it and suggests the general shape of preemphasized digital signals. A simple implemetation in digital transmitters is to increase the first “one” of every sequence of “ones”. This increase is on the order of 30% and needs to be adjustable in order to accommodate different path lengths. A more advanced form is to increase, by varying degrees, the magnitudes of several first digits in all sequences of contiguous “ones”. The disadvantages to this technique are limited availability and accentuated cross talk. The first is likely to ameliorate with time; the second can be remedied with better design. Performance predictions for various implementations are, again, carried out and optimized in software.



None of the signal conditioning approaches are perfect or complete, especially that the implementations in the transmitters may vary from manufacturer to manufacturer. The natural questions to ask, then, are:

1) Given that a form of signal conditioning is inadequate for some critical nets, can another form be added to eke out additional performance in order to improve, for example, performance margin?

2) Can several spectral characteristics and several forms of signal conditioning, all within one net, be adequately modeled such as to obtain an accurate, optimized prediction of performance?

The answer is yes to both questions with the caveat that the design must start with accurate spectral characteristics, as has been stressed throughout this presentation.

The above example is shown in order to illustrate the effectiveness of preemphasis, PRE; combination of preemphasis with empirically estimated values of the equalization components, PRE & EMP; and, preemphasis with optimally determined values of the equalization components.

Preamplification at the receiver suggests itself from the above illustrations as a third form of active signal conditioning. Since the signals in the lower right corner can be thought of as having a high signal-to-noise ratio, a simple flat band or notch preamplifier can be placed in front of (or designed into) the receiver without the risk of saturating it. The disadvantage of boosting cross talk with preemphasis is removed with this approach.

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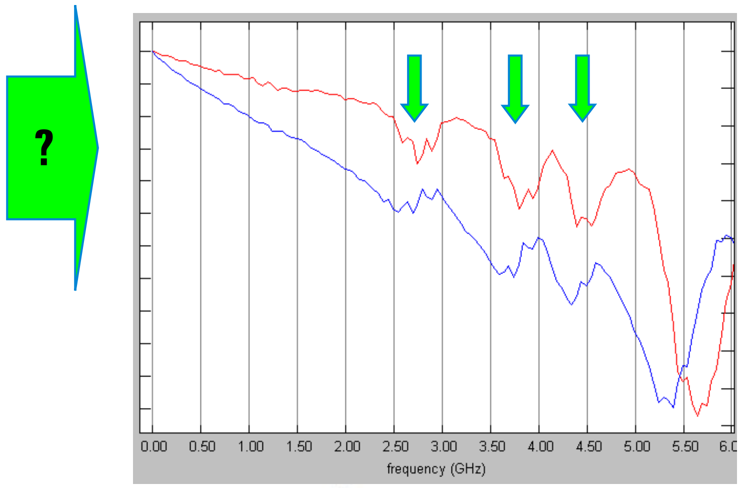
Connector Spectral Characteristics

Generic

0.20
to
2dB



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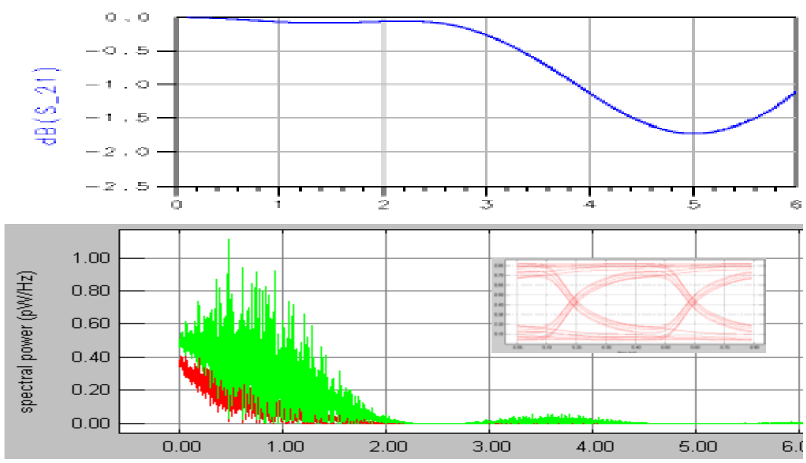
Compared to circuit boards and especially backplanes or motherboards, interconnection products are relatively small and, when well engineered, do not contribute significantly to resistive damping, whether within the dielectrics or the conductors of which they are made.

Instead, the spectral characteristic, as shown for example above, is nearly totally defined by the geometric complexity of the structure. Both amplitude and phase are affected by physical intricacies. In right angle connectors, skew is frequently present. But, when tolerancing is very strict and manufacturing practices are high quality, the built in skew is well characterized and can be considered to be fixed, with only minor statistical variations. Such fixed skew can be easily compensated in the design phase.

Typically, there is a sequence of reflective resonances as illustrated above. Given sufficient reflective strength, any one of these can preclude successful utilization beyond that frequency.

A “Good” Connector Characteristic: IB

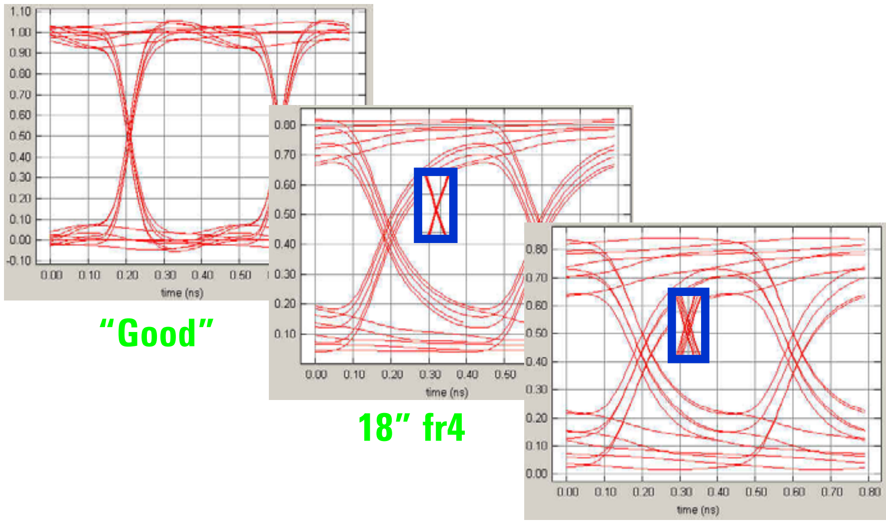


The above spectral characteristic is indicative of a design which has been carried out with attention to detail and clearly aims at the high speed application. The most significant feature is that nearly all energy is transmitted up to 2.5 GHz and more than 95% voltage signal is transmitted at 3 GHz. Moreover, the first reflective peak, located at 5 GHz, is well below the 3 dB point . This characteristic is provided courtesy of ERNI Components Corporation, Richmond, Virginia.

The spectrum of a PRB sequence at 2.5 Gb/s is displayed for comparison. The green shows the transmitter spectrum and the red shows the diminished spectrum of a signal propagated in FR4 until such time that only 50% of the eye amplitude reaches the receiver. The spectrum of the propagated signal is especially well contained within the high transmission portion of the connector.

Note that the spectrum of a 5 Gb/s PRBS would be largely located to the left of 2.5 GHz and would be relatively mildly affected by the resonance peak located at 5 GHz.

“Good” Connector @ 2.5 Gb/s in fr4



“Good”

18” fr4

COMP

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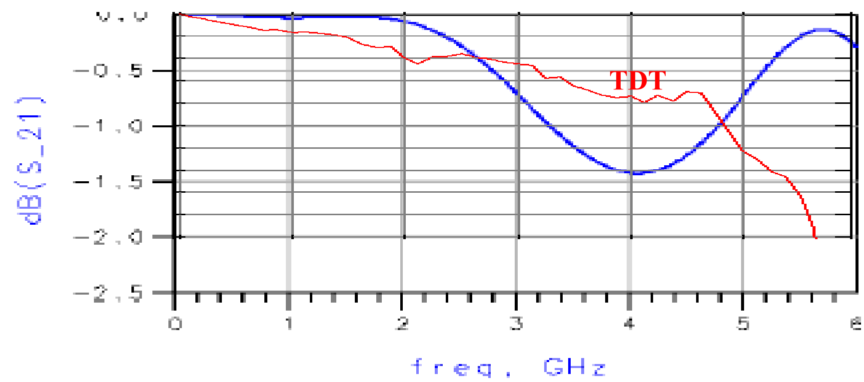
The longer path in fr4 affects the signal significantly. Nevertheless, restoration of timing integrity with signal conditioning remains strong.

ERmetZD: TDT Extraction

Measurement-Based Design Process



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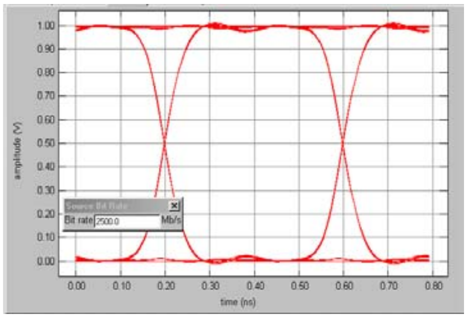
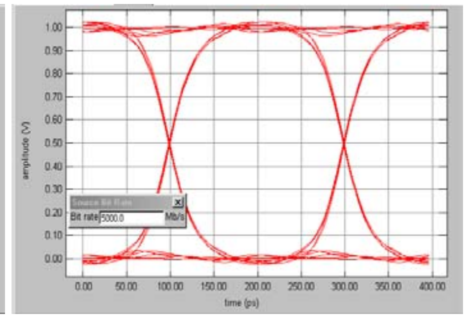
ERmetZD @ 2.5 and 5.0 Gb/s

Measurement-Based Design Process



2.5 Gb/s



5.0 Gb/s

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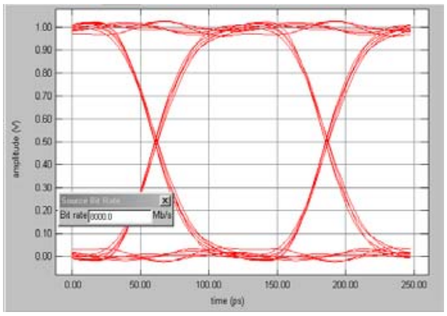
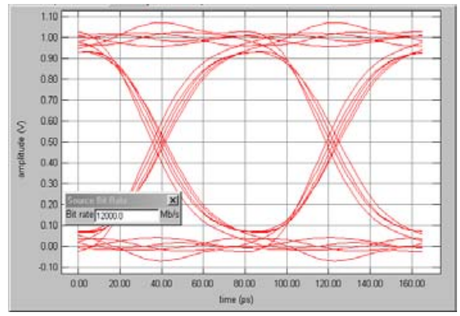
ERmetZD @ 8.0 and 12.0 Gb/s

Measurement-Based Design Process



8 Gb/s



12.0 Gb/s

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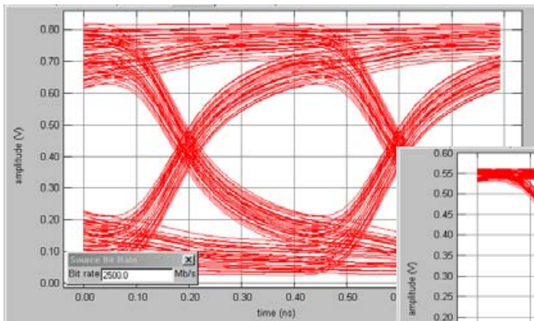
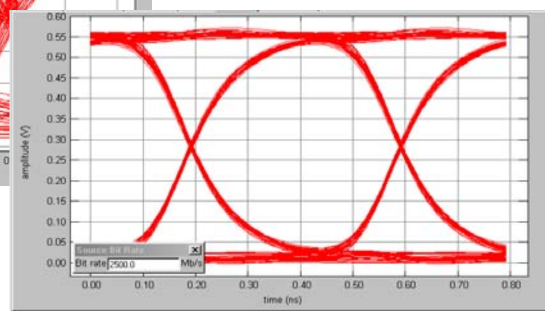
Effect of Signal Conditioning @ 2.5 Gb/s

Measurement-Based Design process

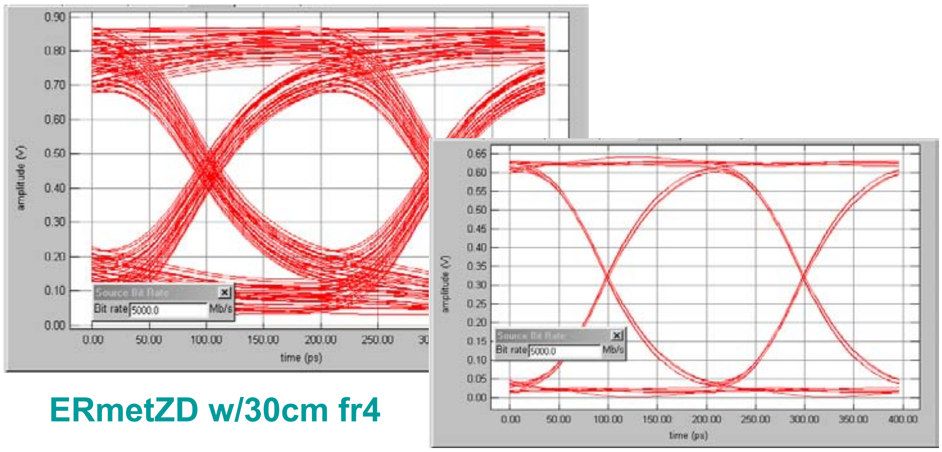


ERmetZD w/50cm fr4



Effect of Signal Conditioning @ 5.0 Gb/s

Measurement-Based Design Process



ERmetZD w/30cm fr4

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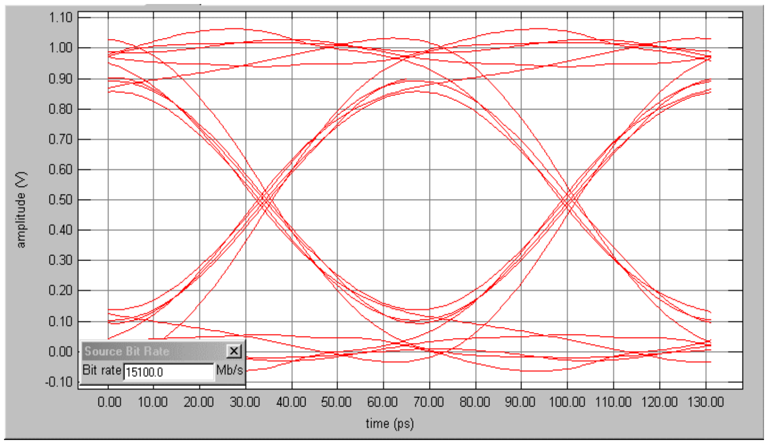
3dB EPD of ERmetZD: ~15.0 Gb/s

Measurement-Based Design Process



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Resources: Agilent

For the Measurement-Based Design Process

- TDR/TDT Measurement System (with Oculus SW)
- Vector Network Analyzer
- ATN Microwave VNA System

For the Design Validation, Verification Process

- InfiniBand Traffic Generator/Analyzer
- High Speed Logic Analyzer
- Multichannel Programmable Data Generator
- High Speed Pulse Generators (1.32 & 3.0 Gb/s)

This presentation on measurement-based design relies on a number of resources that can either capture the subtlety of broadband spectral dependence, such as the TDR/TDT (with Oculus) or the Vector Network Analyzers, or validate the integrity of design with such instruments as the high speed pulse generator or the logic analyzer.

Advances continue to be made on all instruments such as to make them more accurate, operate at higher speeds, achieve higher resolution or, simply, present a simpler and friendlier interface. To this end, more and more instruments are based on a true windows operating system platform so that they are menu driven and are not more difficult to use than a laptop. As another example,recent improvements on logic analyzer cards have reduced the timing adjustment from 100 ps to 10 ps and the setup and hold time from 1.25 ns to 500 ps.

Resources: atSpeed Technologies

- Specializes in advanced issues of design
- Services for design, new technologies
- Offers SI/Emissions Seminars at all levels
- Specializes in high perf. interconnections
- High speed measurements, fixturing, probing
- Design Software Author: Oculus, Matrix Cascade, Matrix Conversion, Equalization Opt., Preemphasis Optimization.

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atSpeed staff is particularly experienced in addressing advanced design and measurement issues at high speed and, with Agilent participation, have developed a leadership position in the measurement-based design approach for high performance. Members of its staff have contributed significantly to the advances in design throughout many years in the form of numerous publications and software, custom as well as commercial.

Conclusion: IB Architecture Phys. Layer

- Advances in design, measurement-based design are serving the early IBA well.
- Advanced design methods can continue to keep costs down by enabling implementation in established, low cost technologies.
- Success requires additional design discipline.

Conclusion: forecasting

We are at the threshold of unprecedented data rates in copper and pcb technologies (the seven lives of pcb). Nevertheless:

- Digital signal conditioning r&d is at its infancy.
- Emerging signaling (ML) is not widespread.
- High performance connectors are exceptions.
- Need libraries of broadband characteristics.
- Need acceptance of advanced design methods.

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FIN

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