Application Note

Cost-Efficient Cable Assembly Compliance Testing and Modeling

Cable and connector assemblies are becoming a critical piece of system design at gigabit speeds in XAUI, Infiniband, PCI Xpress, Serial ATA and Gigabit Ethernet. With increased signal speeds, new specification-compliance testing procedures for cables and cable-connector assemblies have become more and more complex, and now include both time-domain (impedance, skew, delay) and frequency-domain (insertion, return loss) tests. Eye-diagram testing also becomes a key requirement for cable and connector manufacturers.

In the present business environment, cost savings are crucial for the cable assembly houses, placing a heavy focus on cost-effective test equipment sets to perform tests required in high-speed specifications. Conventional equipment will not effectively address these issues, but new technology, currently available, offers a 3X savings over typical methods. In addition to cost savings during the compliance testing phase, additional functions - such as creating SPICE / IBIS models for the cables and connectors, including the frequency-dependent loss - can be achieved with no additional cost using the defined set of equipment.

Time domain tests

As stated above, a typical set of time domain tests includes impedance, delay, skew, rise rime degradation, and time domain crosstalk. These tests are normally done with a TDR oscilloscope. The procedures for these tests are well documented in the industry specifications, see reference [1]-[3], and vendor-specific test procedures [4]-[5], and will not be discussed here. Because the requirement for these tests has been around for some time, most cable assembly manufacturing facilities already own a TDR oscilloscope required to perform these tests. This already existing investment in a TDR oscilloscope makes it logical to base the required specification testing on the TDR platform.

Frequency domain and eye diagram tests

Frequency-domain tests, such as insertion loss, return loss, and frequency domain crosstalk, have been increasingly added to the recently released signaling specifications in the industry. In addition, an eye diagram mask testing has become part of every new specification. These tests are traditionally done with a vector network analyzer (VNA). Since all the new signaling standards are differential, a differential vector network analyzer is required to perform these tests.

To measure the eye, the test engineer can employ the sampling channels of the same TDR oscilloscope used for the suite of time domain compliance tests. However, a cable, unlike an active component, cannot generate the required test pattern by itself. Therefore, there is a need for a pattern generator operating at gigabit speeds.

A differential vector network analyzer and a gigabit pattern generator can be an expensive addition to the instrument set required for compliance testing of a cable assembly. There is a way, however, to avoid the additional expense, while still meeting the required specifications.

Frequency domain tests

Insertion loss (S21) is one specification that requires frequency domain measurement. Sometimes specifications also require return loss (S11) and frequency domain crosstalk measurements. Because all of the new signaling standards are differential, these measurements must be performed in differential mode.

The techniques for measuring S-parameters from TDR/T measurements, often referred to as Time Domain Network Analysis (TDNA), have been extensively researched and reported, [6], [7]. With the use of these techniques, we can leverage the TDR equipment already owned by most cable manufacturing facilities, and perform the required insertion loss, return loss, and frequency domain crosstalk tests. Below is an example of an insertion loss measurement, obtained from a TDR oscilloscope differential transmission measurements, and converted into the insertion loss using TDA Systems' IConnect®

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software, which employs the techniques mentioned above.

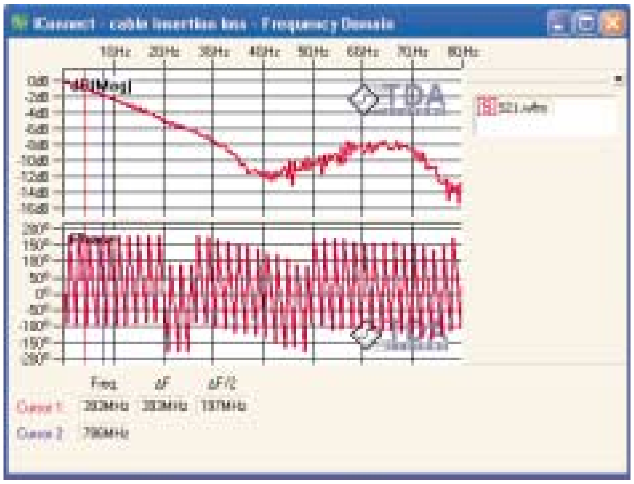


Figure 1. Cable insertion loss measured using TDT measurements. Data courtesy Molex, Inc.

The dynamic range obtained with the TDR oscilloscope is less than the dynamic range of a vector network analyzer. It is also worth noting that one can improve the dynamic range of a TDR oscilloscope by using digital averaging, which plays the same role as narrow-band filtering in frequency domain. With TDR, and a sufficient number of averages, we can obtain perhaps 50dB of dynamic range, whereas a properly used VNA is capable of 100 dB or more of dynamic range. However, consider that a typical insertion loss specification for any of the digital standards mentioned above is in the area of about -10 to -15dB, whereas a typical frequency domain crosstalk test is about -30dB. Therefore, it is clear that as important as it is to have high dynamic range for testing of microwave components such as narrowband filters, testing of cable assemblies destined for a high-speed digital application is very well served by the TDR oscilloscope with the appropriate TDNA software. Within the dynamic range specified, the data from a TDR oscilloscope will match the data from a VNA very well. If one uses a standard TDR plug-in currently available on the market from Agilent or Tektronix, useful S-parameter data up to approximately 12 Ghz can be obtained, which covers pretty much most mainstream signaling standards, see Figure 2.

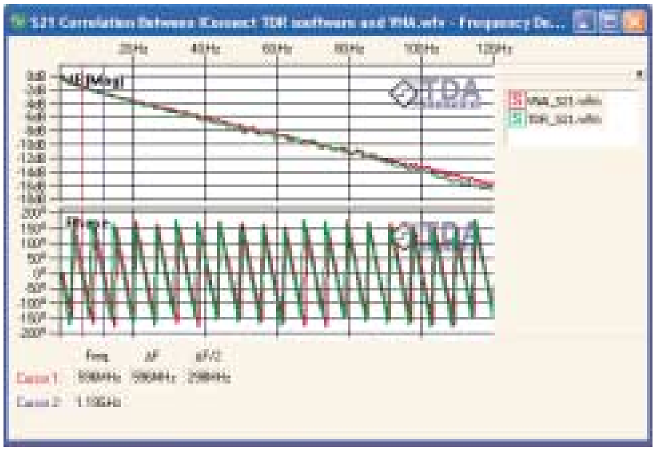


Figure 2. Insertion loss (S21) measurement correlation between differential TDR and IConnect software vs differential VNA

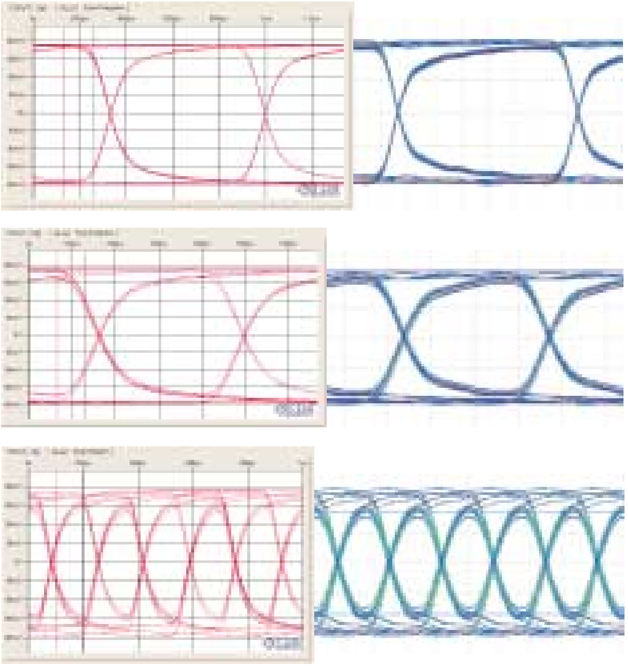
For applications such as 10 Gbit and 40 Gbit Ethernet, where a wider frequency range of S-parameter data may be required, the user can employ a differential module from Picosecond Pulse Labs, which provides a substantially faster rise time, and extends the usability of TDR-based S-parameters to the abovementioned frequencies. Alternatively, a differential VNA with the appropriate frequency range may be used to cover those speeds.

Interestingly, since the TDNA S-parameter measurement procedure can involve much less calibration than a VNA based one, the test engineer can de-embed the fixture much easier with TDNA measurement. If the reference open waveform, which is the minimum reference measurement required to obtain S-parameters from TDR/T measurements, is acquired at the end of the test fixture, rather than at the end of the SMA cable connected to the fixture, the fixture is effectively de-embedded from the measurement. To achieve the same with a VNA approach, one would have to follow a multi-step de-embedding procedure, and have precision calibration standards at the end of the fixture itself.

Eye diagram tests

The eye diagram test is another key measurement required by most new communications and computer signaling standards. The measurement of the eye diagram for an interconnect captures the deterministic jitter in the interconnect, which is caused by losses and inter-symbol interference (ISI) in the interconnect. Because of this fact, the TDR measurements of a cable assembly contain all the information required to re-construct this deterministic jitter, and the eye diagram computed from the time domain transmission (TDT) measurements using a TDR oscilloscope is as valid and accurate as the eye diagram obtained using a pattern generator and a sampling oscilloscope.

The following pictures illustrate this statement by showing examples of Serial ATA eye diagram cable tests using IConnect TDR software and TDT measurements (left on each picture) and the eye diagrams using a pattern generator. The eye diagram was generated at 1.5Gbit/sec, 3Gbit/sec and 6 Gbit/sec data rates. The eye openings are clearly identical, since only deterministic (loss and ISI-related) jitter exists in the cable interconnects.



TDT-based

Pattern generator based

Figure 3. Correlation between measured and simulated eye diagram degradation due to interconnect performance at Serial ATA Generation 1, speed 1.5Gb/s; Generation 2, speed 3Gb/s; and Generation 3 speed 6.0Gb/s. Data courtesy Molex, Inc.

Similarly to the S-parameter measurement discussion, since in the reference waveform for the TDR based measurement can be acquired at the end of the fixture, the effects of the fixture itself can be removed from the eye diagram, thus allowing a more accurate eye diagram measurement results. This easy fixture de-embedding is not possible as easily with a pattern generator, and the additional jitter in the fixture may account for some apparently larger jitter amount in the pattern generator-based eye diagram of the cable assembly. Thus, a pattern generator based eye for a passive component such as a cable assembly may actually produce an eye that is degraded by the fixture, and as such is worse than the actual eye degradation produced by the cable assembly itself.

Cable Assembly Modeling

Even though a model for a cable assembly is not required by most specifications, providing such model could provide a competitive edge for a cable or cable assembly company. Such modeling will not necessarily be performed on a production floor, but can be efficiently done in an R&D environment or in an application support group. Again, the modeling system based on a TDR oscilloscope together with IConnect software provides the efficient approach to modeling both the connectors and the losses in the cable itself [8].

Each connector differential pair is best modeled with the Z-line impedance profile approach. This approach allows the designer to obtain a coupled model for the connector in question. Furthermore, the cable can be modeled using the lossy line model, which allows us to include the frequency dependent losses of the cable in the model. As a result, we can obtain a complete and accurate model for the complete cable assembly, enabling the designer to accurately simulate the cable assembly performance as a part of the overall system level simulation.

Model listing for the mated connector (without the cable) is given below. An alternative lumped model can be easily generated as well. However, the designer must keep in mind that for such a model to be valid, each LC subsegment must be shorter than the rise time of the signals with which this model is to be used.

```
* TDA Systems:  IConnect
.subckt ConnMdl port1 port2 port3 port4 gnd_
****** Partition #1
t1  port1  gnd_  1  gnd_ Z0=92 TD=53.4p
t2  port3  gnd_  2  gnd_ Z0=92 TD=53.4p
t3  port1  port3  1  2 Z0=318 TD=53.4p
****** Partition #2
t4  1  gnd_  3  gnd_ Z0=98.8 TD=50p
   t5  2  gnd_  4  gnd_ Z0=98.8 TD=50p
   t6  1  2  3  4 Z0=160 TD=50p
***** Subsegment #1 *****
   t7  3  gnd_  port2  gnd_ Z0=62.3 TD=111p
   t8  4  gnd_  port4  gnd_ Z0=62.3 TD=111p
   t9  3  4  port2  port4 Z0=396 TD=111p
.ends
```

The validation for the connector model is given for the even and odd mode of propagation, which ensures model correlation for these two modes also ensures accurate simulation of any kind of signal propagating through the connector.

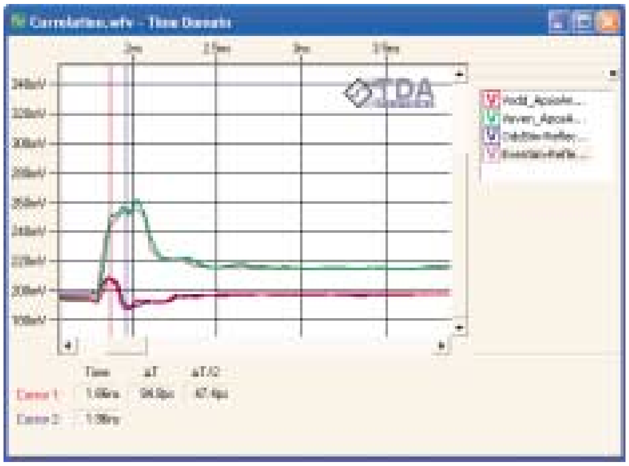


Figure 4. Correlation between the even and odd mode measurements of the connector and the model simulations.

A lossy line model for the cable assembly was also extracted via TDR/TDT measurement. Such model can be used to predict the eye diagram as well as the insertion loss via simulations. A cable coupled lossy line model is shown below.

```
.MODEL Lossy_Mdl W MODELTYPE=RLGC N=2
+ Lo=2.5e-007 3.6-008 1.27e-006
+ Co=9.97667e-011 -8.21e-012 9.97667e-011
+ Ro=1.48 0.1826 1.48
+ Go=0 0 0
+ Rs=0.00015 0.0000957 0.00015
+ Gd=1.06667e-011 0 1.06667e-011
.ends
```

The overall correlation of the model simulation to the measurement is shown in Figure 5 below. Providing a customer with a model with this level of correlation will provide a valuable competitive edge to the cable assembly manufacturer.

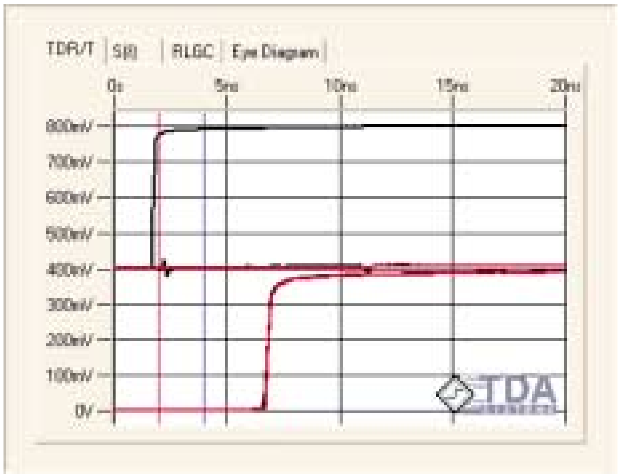


Figure 5. Correlation of the lossy line model for the odd mode of propagation in the cable.

Summary

We have demonstrated the economical approach to cable assembly testing, where a single piece of test hardware - Tektronix or Agilent TDR oscilloscope, coupled with the IConnect software from TDA Systems, can be used to complete a full suite of tests for the cable assembly on the production floor, from cable impedance, to insertion loss and eye diagram.

The cost savings achieved through this approach can be very substantial, decreasing the cost of required equipment by an order 3-5X at the SATA or PCI Xpress speeds, and by the order of 10X at the 10Gbit speeds.

Bibliography

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[3] SFF-8416 Specification for Measurement and Performance Requirements for HPEI (High Performance Electrical Interconnect) Bulk Cable (draft), SFF Committee

[4] "TDR Impedance Measurements: A Foundation for Signal Integrity," Tektronix Application Note 55W-14601-0

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[8] "Signal Integrity Modeling of Gigabit Backplanes, Cables and Connectors Using TDR" - EDN Magazine, July11, 2002

Acknowledgements

TDA Systems wishes to acknowledge help from Michael Cheong, Molex Regional Technical Marketing Manager for his help with collecting data and supplying samples of Molex Serial ATA cable assemblies. He can be reached for questions at: michael.cheong@molex.com.

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