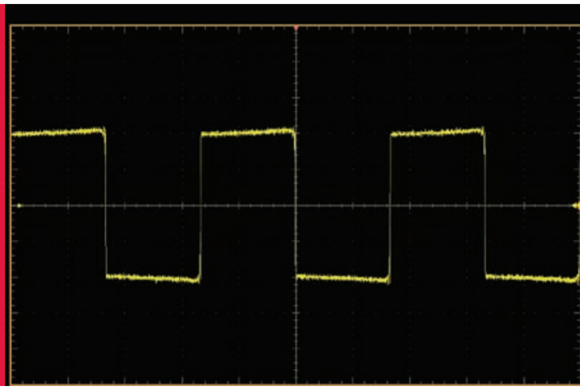


Physical Layer Compliance Testing for 10GBASE-T

Application Note

Introduction

Rising demand for broadband networks has driven adoption of faster Ethernet technologies. This application note explains proper electrical testing approaches for 10GBASE-T designs using Tektronix oscilloscopes. To provide technical context behind the testing approach, included in this note is a history on the IEEE Ethernet variants, and background on protocol and PHY layer architectures of the popular standard.

Tektronix®

Copper Based	Optical	Backplane	CX4	PoE / PoE+
10, 100, 1000 , 10GBase-T	10GBASE-SR, 10GBASE-LR, 10GBASE-ER, 10GBASE-SW, 10GBASE-LW, 10GBASE-EW, 10GBASE-LRM	10GBASE-KR, 10GBASE-KX4	10GBASE-CX4	10, 100, 1000Base-T Cat3/Cat5e
802.3i, 802.3u, 802.3ab, 802.3an	802.3ae, 802.3aq(10 Gb/s)	802.3ap	802.3ak	802.3af
Ethernet over twisted pair cable. T568A or T568B (10 & 100BASE-T), Cat 5 & above for 1000 & 10GBASE-T	Ethernet over Optical cables	A backplane is a circuit board that connects several connectors in parallel to each other, so that each pin of each connector is linked to the same relative pin of all the other connectors forming a computer bus.	Transmits over 4-lanes in each direction over copper cabling similar to the variety used in InfiniBand technology	Power over Ethernet or PoE technology describes a system to transfer electrical power, along with data, to remote devices over standard twisted-pair cable in an Ethernet network
Low cost widely available	Optical modules are defined multisource agreement and not IEEE. XFP, XFI, SFP+, XENPAK, X2, XPAK	Backplanes are normally used in preference to cables because of their greater reliability	Each lane of the copper carries 3.125 Gbaud of signaling bandwidth. It is designed to work up to a distance of 15 m	PoE – Maximum power up to 15.40W. PoE+ - Maximum power up to 24W
PC, Servers	SDH/SONET, Data Centers	DIN 41612 connectors used in the VMEbus & other connections used on motherboard	Server Market	WiMAX, Zoom Cameras, Videophones, Thinclients, Wireless LAN access points

Table 1. Ethernet PHY Media variants.

Background on the 10GBASE-T Standard

The IEEE 802.3an standard defines the wire-level modulation for 10GBASE-T as a Tomlinson-Harashima Precoded (THP) version of pulse-amplitude modulation with 16 discrete levels (PAM-16), encoded in a two-dimensional checkerboard pattern known as DSQ128.

10 Gigabit Ethernet over horizontal structured, twisted-pair copper cabling, 10 Gigabit Ethernet MAC and media independent interface is specified in IEEE 802.3an-2006. Copper cabling remains the medium of choice for network managers for horizontal cabling. Due to the continued predominance of copper cabling, top industry experts spent four years developing the IEEE 802.3an-2006 standard so that the result offers the best cost performance trade-offs over the widest range of media. By delivering 10GBASE-T networking solutions, the IT industry allows network managers to scale their networks to 10 Gigabit speeds while leveraging their investment in installed copper cabling infrastructure. In addition, for new installations, network managers can continue to leverage the cost-effectiveness and plug-and-play simplicity of copper structured cabling through the benefits of 10GBASE-T technology. Above in Table 1 is an overview of the different Ethernet variants as viewed from the PHY Media.

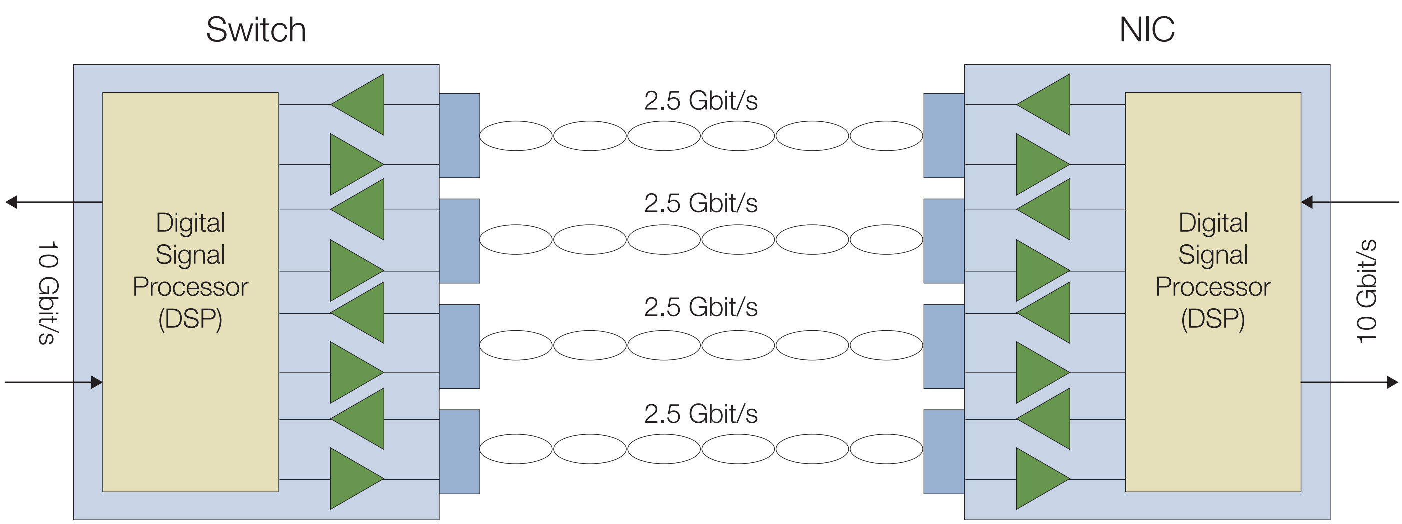


Figure 1. 10GBASE-T network running on copper.

1000BASE-T	10GBASE-T
5-level coded PAM signaling (2 information bits/symbol)	Baseband 16-level PAM signaling (3.125 information bits/symbol)
8-state 4D Trellis code across pairs	128-DSQ + LDPC(2048, 1723) Tomlinson-Harashima precoder at Tx
Full duplex echo-cancelled transmission	Full duplex echo-cancelled transmission
125 Mbaud. ~80 MHz used bandwidth	800 Mbaud. < 500 MHz used bandwidth
FEXT Cancellation recommended	FEXT Cancellation required

Table 2. Source: Solarflare Communications, Inc.

The 10GBASE-T PHY employs full duplex baseband transmission over four pairs of balanced cabling. The aggregate data rate of 10 Gb/s is achieved by transmitting 2500 Mb/s in each direction simultaneously on each wire pair as shown in Figure 1.

Baseband 16-level PAM signaling with a modulation rate of 800 Megasymbol per second is used on each of the wire pairs. Ethernet data and control characters are encoded at a rate of 3.125 information bits per PAM16 symbol, along with auxiliary channel bits. Two consecutively transmitted PAM16 symbols are considered as one two-dimensional (2D) symbol. The 2D symbols are selected from a constrained constellation of 128 maximally spaced 2D symbols, called DSQ1287 (double square 128). After link startup, PHY frames consisting of 512 DSQ128 symbols are continuously transmitted. The DSQ128 symbols are determined by 7-bit labels, each comprising 3 uncoded bits and 4 LDPC-encoded bits. The 512 DSQ128 symbols of one PHY frame are transmitted as 4 X 256 PAM16 symbols over the four wire pairs. Data and Control symbols are embedded in a framing scheme that runs continuously after startup of the link. The modulation symbol rate of 800 Msymbols/s results in a symbol period of 1.25 ns.

Optical 10 Gigabit and 10GBASE-CX4 which use non-standard, short-reach, 15 meter InfiniBand™ cabling, are deployed today primarily for switch-to-switch links and switch-to-server links in high-performance computing clusters. This market, while growing, is small. Although 10G Ethernet has been shipping since 2001, in 2006 a relatively modest 30,000 10G optical and CX4 switch ports shipped. Compare this to the 5 to 6 million 1G copper switch ports (1000BASE-T) which ship each month.[1] 10GBASE-T switches and 10GBASE-T servers can dramatically expand the opportunity for 10G Ethernet networking by supporting simpler, cheaper, twisted-pair copper cabling necessary for the expansion of 10G networking beyond high performance computing into commercial data centers and enterprise networks. See Figure 1 10GBASE-T network running on copper above.

Table 2 illustrates the similarities and difference between 1000BASE-T and 10GBASE-T Ethernet.

[1] Dell's Oro Group, Ethernet Switching Report.

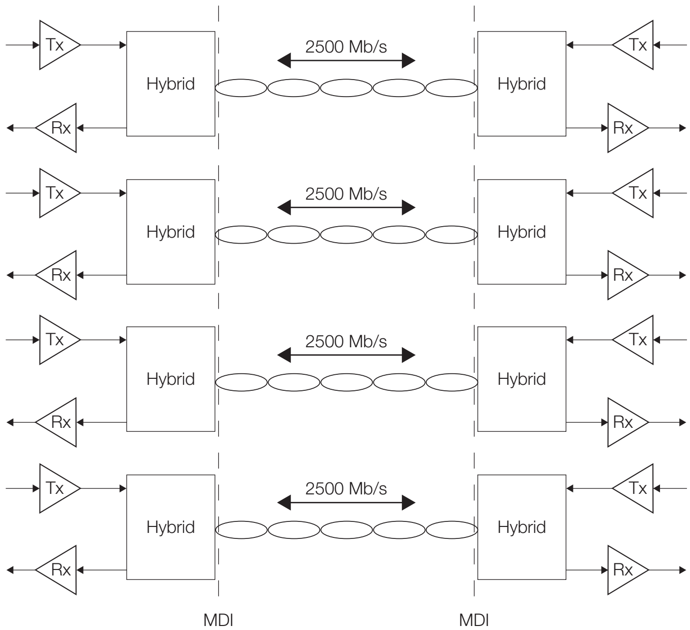


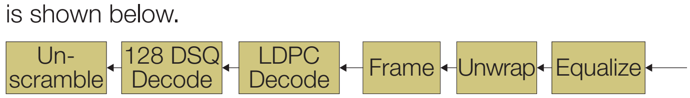
Figure 2. 10GBASE-T topology.

PHY Signaling Approach

Now that we have a good background on the standard's development, let's take a look at the Physical Signaling approach for 10GBASE-T. This will help to build a better basis for testing and verification approaches later in this application note. For starters, in Figure 2 is the general topology for 10GBASE-T; note the 4 X architecture approach used.

For the datapath, the 10GBASE-T standard meticulously defines what the transmitter has to do.

The receiver implementation is left almost entirely up to the individual chip manufacturer. A typical line up for the receiver is shown below.



Despite numerous improvements in the UTP cable, every "trick in the book" of signal processing needs to be employed to achieve 10 Gb/s over 100m of CAT-6a cable. To meet some of the challenges, the 802.3an-2006 standard utilizes some of the techniques listed below:

- **Self-synchronizing scrambler -** Provides clock transitions, and a statistically random power spectrum for EMI control, equalizer convergence, etc.
- **DSQ 128 coding -** The 10GBASE-T standard uses a synthetic 2-dimensional 128 DSQ (Double SQuare) constellation, which conveys 7 bits per symbol.
- **LDPC (Low Density Parity Check) block codes -** Block codes are one of two kinds of error correcting codes that can be used to approach the Shannon capacity of a channel.
- **Tomlinson-Harashima Precoding (THP) -** The 10GBASE-T standard calls for the use of THP, which is a scheme in which the equalizer for the channel is placed in the transmitter theoretically allowing the receiver to see "perfect" symbols. Training is accomplished during the initialization phase of the link.

Cross Talk Challenges

Another challenge is cable cross. The following methods are employed to reduce cross talk.

- An aggressive twist - Varying the twist ratios between the 4 pairs to minimize coupling at specific wavelengths.
- Increasing the diameter of the cable to reduce crosswalk from neighboring cables (alien crosswalk).
- Using geometry-control techniques.

1000BaseT - Measurements	10GBaseT - Measurements
Peak voltage, Amplitude symmetry, Droop	Linearity, Droop, Clock frequency measurement
Jitter with Tx clock, Filtered, Unfiltered, as master and slave (300psec)	Master Jitter and slave Jitter (5psec RMS)
Distortion test limit is 10mV	Power spectral density measured to be within upper and lower limit of the mask
Return Loss (100 MHz)	Return loss (500 MHz)
Measurement are performed on all four pairs	All the measurements are performed on all four pairs except slave Jitter which is performed only on Channel D

Table 3. PHY Testing – Similarities and differences between 1000BASE-T & 10GBASE-T.

PHY Layer Challenges of 10GBASE-T Electrical

The 10GBASE-T PHY is one of the 10 Gigabit Ethernet family of high-speed CSMA/CD network specifications. The 10GBASE-T Physical Coding Sub layer (PCS), Physical Medium Attachment (PMA), and baseband medium specifications are intended for users who want 10 Gb/s performance over balanced twisted-pair structured cabling systems. 10GBASE-T signaling requires four pairs of balanced cabling.

Various challenges exist as 10 Gigabit Ethernet is extended beyond its initial role as a fiber only solution. Achieving 10 Gbps on copper unshielded twisted pair (UTP) cabling is a significant technical achievement. Meeting the application's requirements for low power is also needed for 10GBASE-T, to meet its full potential. Near Shannon limit performance leverages multiple techniques, from pre-coding to a DSQ128 multi-level signaling. Intriguing technologies are the Error Control Code and the Low Density Parity Check (LDPC). Together these techniques permit operation at close to the Shannon limit. There are tradeoffs involved in achieving this goal, but power and latency are kept at acceptable levels. Table 3 shows the similarities and differences between 1000BASE-T and 10GBASE-T.

Physical Layer Compliance Testing for 10GBASE-T PHY

There are 6 primary measurement clauses in the IEEE 802.3 spec that reference PHY testing. What follows is a review of the test setups and results screens using TekExpress 10GBASE-T Automated Compliance Software running on a Tektronix DSA70000 Series Oscilloscope.

The measurement clauses standard reference descriptions are:

- IEEE 802.3an-2006 Subclause 55.5.3.1
  Maximum output droop
- IEEE 802.3an-2006 Subclause 55.5.3.2
  Transmitter linearity
- IEEE 802.3an-2006 Subclause 55.5.3.3
  Transmitter timing jitter
- IEEE 802.3an-2006 Subclause 55.5.3.4
  Transmitter power spectral density (PSD) and power level
- IEEE 802.3an-2006 Subclause 55.5.3.5
  Transmit clock frequency
- IEEE 802.3an-2006 Subclause 55.8.2.1
  MDI return loss

These tests are illustrated in the next section of this application note.

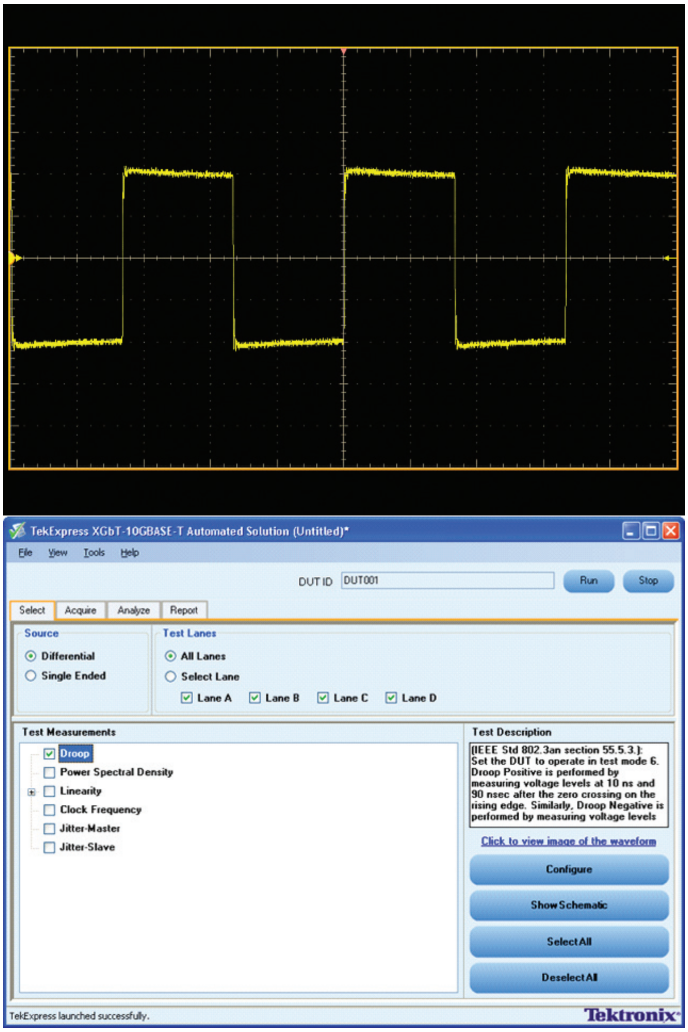


Figure 3. Maximum output droop - IEEE 802.3an-2006 Subclause 55.5.3.1.

Maximum output droop - IEEE 802.3an-2006 Subclause 55.5.3.1

Purpose: To verify that the transmitter output level does not decay faster than the maximum specified rate.

With the transmitter in test mode 6 and using the transmitter test fixture described in section 55.5.2.1 of 802.3an-2006, the magnitude of both the positive and negative droop shall be less than 10%, measured with respect to an initial value at 10 ns after the zero crossing and a final value at 90 ns after the zero crossing.

This test requires the device under test (DUT) to operate in transmitter test mode 6. While in test mode 6, the DUT shall generate a sequence of 128 +16 symbols followed by 128 –16 symbols continually from all four transmitters with the THP turned off.

The magnitude of both the positive and negative droop shall be less than 10%.

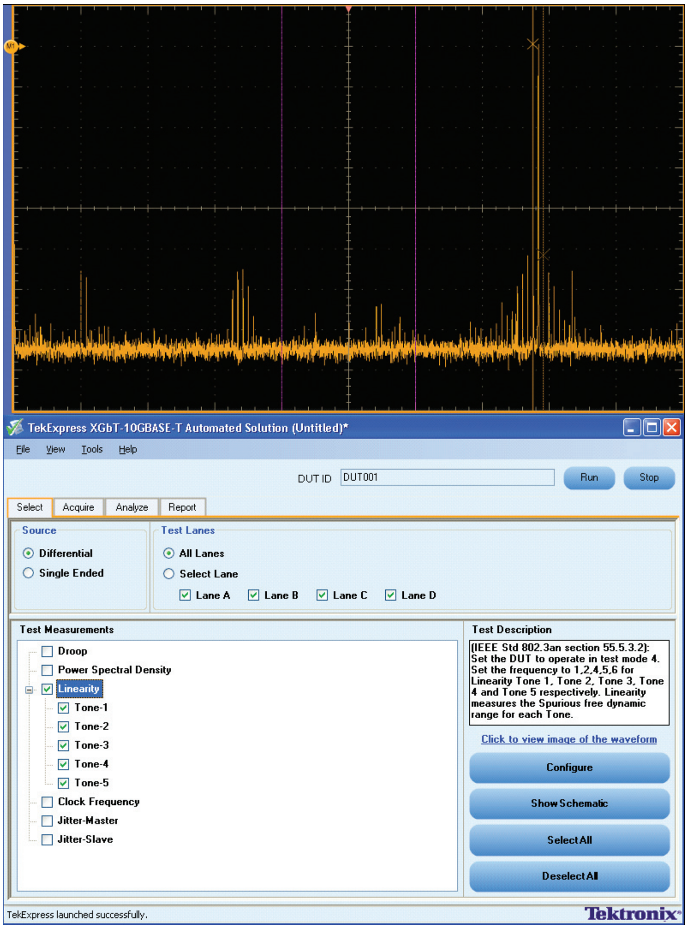


Figure 4. Transmitter linearity IEEE 802.3an-2006 Subclause 55.5.3.2.

Transmitter linearity IEEE 802.3an-2006 Subclause 55.5.3.2

Purpose: To verify that the output of the transmitter conforms to the transmitter linearity mask. Measured on all four lanes i.e. A, B, C & D.

When in test mode 4 and observing the spectrum of the differential signal output at the MDI using transmitter test fixture described in section 55.5.2.1 of 802.3an-2006, for each pair, with no intervening cable, the transmitter linearity mask is defined as follows:

> The SFDR of the transmitter, with dual tone inputs as specified in test mode 4, shall meet the requirement that: $SFDR \geq 2.5 + \min\{52, 58 - 20 \times \log10(f/25)\}$ where f is the maximum frequency of the two test tones in MHz and SFDR is the ratio in dB of the minimum RMS value of either input tone to the RMS value of the worst inter-modulation product in the frequency range of 1 MHz to 400 MHz. This specification on transmit linearity is derived from the requirement for interoperability with the far-end device.

This test needs to be repeated for five test tones as specified in the 802.3an-2006.

XGbT solution uses the oscilloscope as a common platform to perform all measurements including Spectral based measurements like Power Spectral Density, Power Level and Linearity. XGbT – 10GBASE-T Automation solution is less expensive, less complicated and less cumbersome compared to a “Multi Box Solution” which may use an Oscilloscope and a Spectrum Analyzer and therefore provides higher value versus expenditure. XGbT makes use of spectral features on scope to perform these measurements.

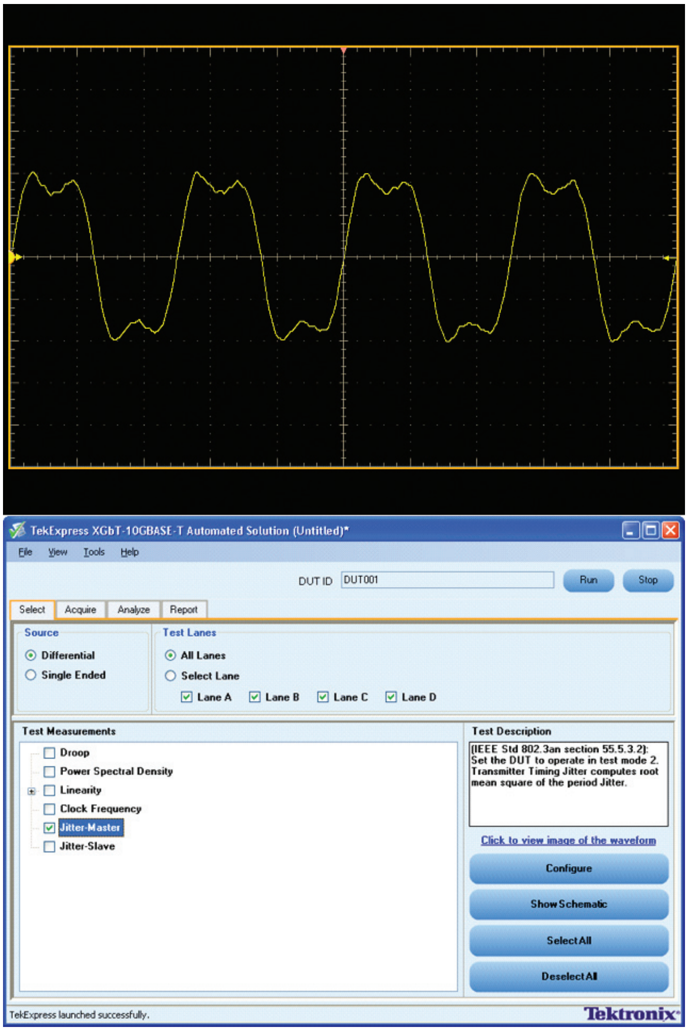


Figure 5. Transmitter Timing Jitter - IEEE 802.3an-2006 Subclause 55.5.3.3.

Transmitter Timing Jitter - IEEE 802.3an-2006 Subclause 55.5.3.3

Case 1 – MASTER transmitter timing jitter

When in test mode 2, the PHY transmits 2 +16 symbols followed by 2 –16 symbols continually with the THP turned off and with no power back off. In this mode, the transmitter output should be a 200 MHz signal and the RMS period jitter measured at the PHY MDI output is less than 5.5 ps. The RMS period jitter is measured as per the test configuration shown in Figure 55-30 of 802.3an-2006 spec over an integration time interval of 1 ms +/- 10%.

Case 2 – SLAVE transmitter timing jitter

For a PHY supporting loop timing mode, the MASTER PHY is set to test mode 1 and the SLAVE PHY is in test mode 3. The MASTER PHY transmits the PMA training pattern (PRBS 33) to the SLAVE PHY on pairs A, B and C, and the SLAVE must synchronize its transmit clock to the signals received from the MASTER PHY. The RMS period jitter measured at the SLAVE PHY MDI output shall be less than 5.5 ps.

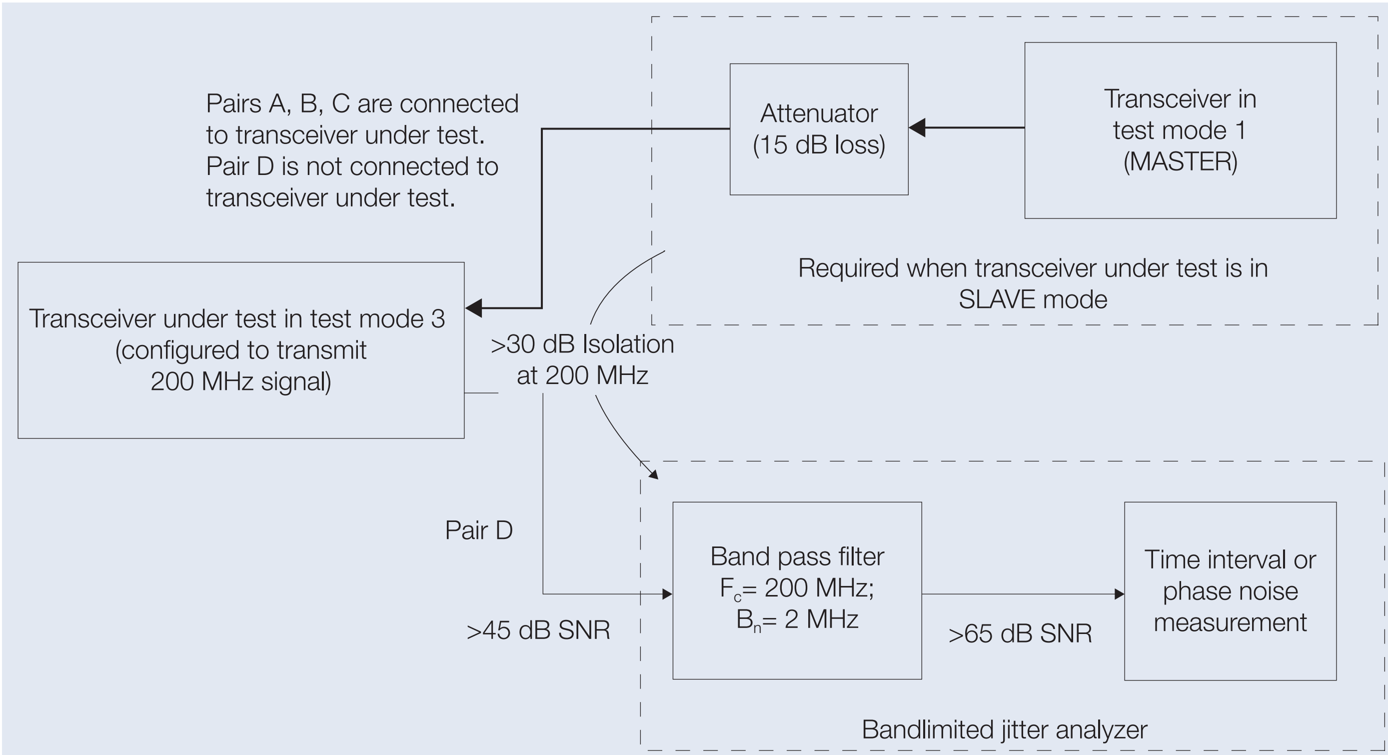


Figure 6. Transmitter test fixture 3 for transmitter jitter measurement.

An appropriate software filter available on each Tektronix oscilloscope is applied to the input waveform. The output of the filter is then computed for the jitter value.

With the transmitter in test mode 2 for Jitter Master and Test Mode 1 & 3 for Jitter slave and using the transmitter test fixture described in section 55.5.2.1 of 802.3an-2006, RMS period jitter measured at the PHY MDI output shall be less than 5.5 ps.

Figure 7. Transmitter power spectral density (PSD) and power level - IEEE 802.3an-2006 Subclause 55.5.3.4.

Transmitter power spectral density (PSD) and power level - IEEE 802.3an-2006 Subclause 55.5.3.4

Purpose: To verify the transmitter power level and power spectral density are within the conformance limits. Measured on all four lanes i.e. A, B, C & D.

With the transmitter in test mode 5 for PSD and using the transmitter test fixture described in section 55.5.2.1 of 802.3an-2006, the transmit power shall be in the range 3.2 dBm to 5.2 dBm and the power spectral density of the transmitter shall fit between upper and lower mask limits described below:

$$\text{Upper PSD}(f) \le \begin{cases} -78.5 \text{ dBm/Hz} & 0 < f \le 70 \\ -78.5 - \left(\frac{f - 70}{80}\right) \text{dBm/Hz} & 70 < f \le 150 \\ -79.5 - \left(\frac{f - 150}{58}\right) \text{dBm/Hz} & 150 < f \le 730 \\ -79.5 - \left(\frac{f - 330}{40}\right) \text{dBm/Hz} & 730 < f \le 1790 \\ -116 \text{ dBm/Hz} & 1790 < f \le 3000 \end{cases}$$

and

$$\text{Lower PSD}(f) \ge \begin{cases} -83 \text{ dBm/Hz} & 5 < f \le 50 \\ -83 - \left(\frac{f - 50}{50}\right) \text{dBm/Hz} & 50 < f \le 200 \\ -86 - \left(\frac{f - 200}{25}\right) \text{dBm/Hz} & 200 < f \le 400 \end{cases}$$

Where f is in MHz.

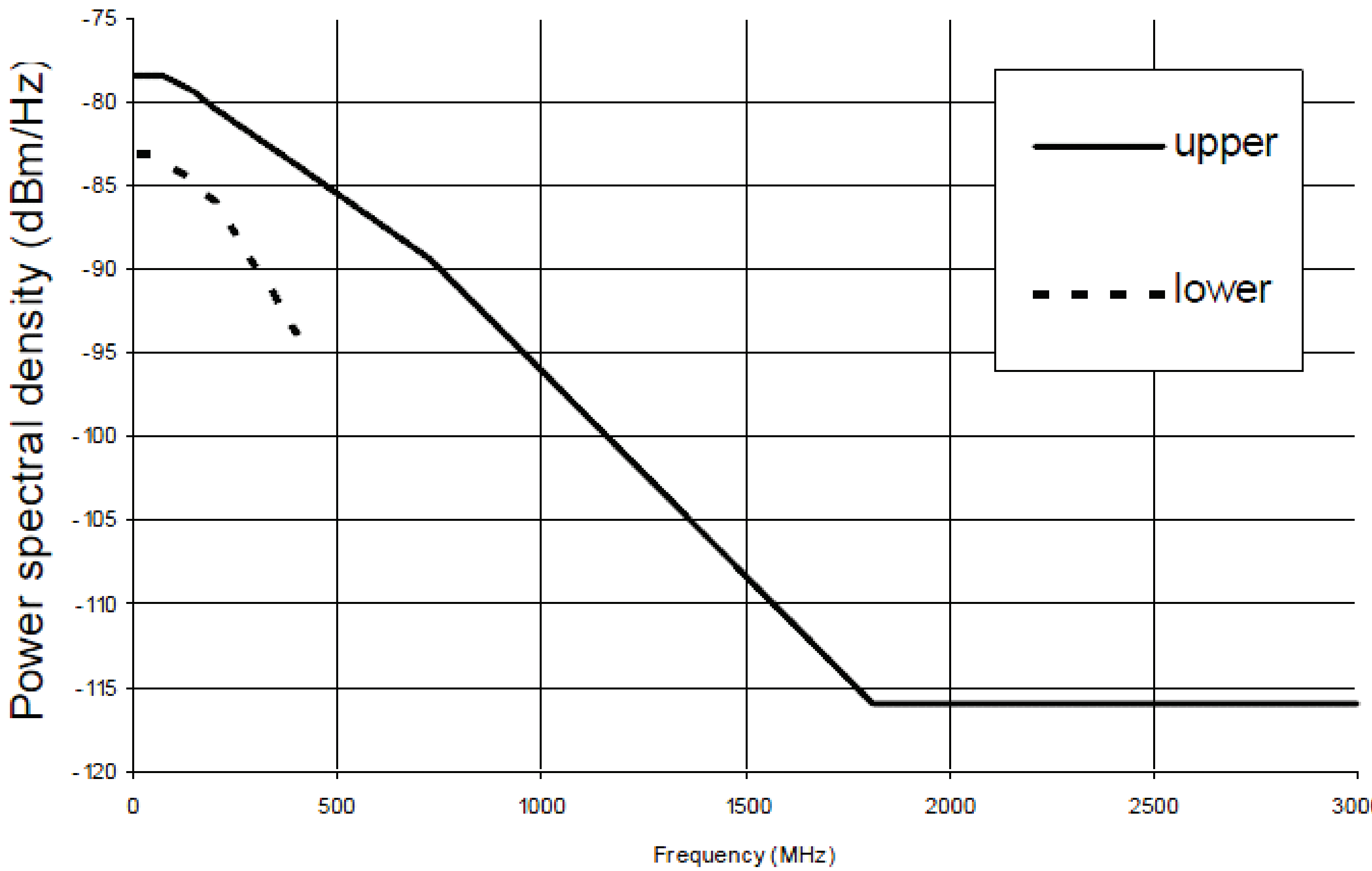


Figure 8. Power Spectral Density measurement.

The XGbT solution uses the oscilloscope as a common platform to perform all measurements including Spectral based measurements like Power Spectral Density, Power Level and Linearity. XGbT is less expensive, less complicated and less cumbersome compared to a “Multi Box Solution” which may require an Oscilloscope and a Spectrum Analyzer, to perform the needed tests. XGbT makes use of spectral features on the oscilloscope to perform these measurements.

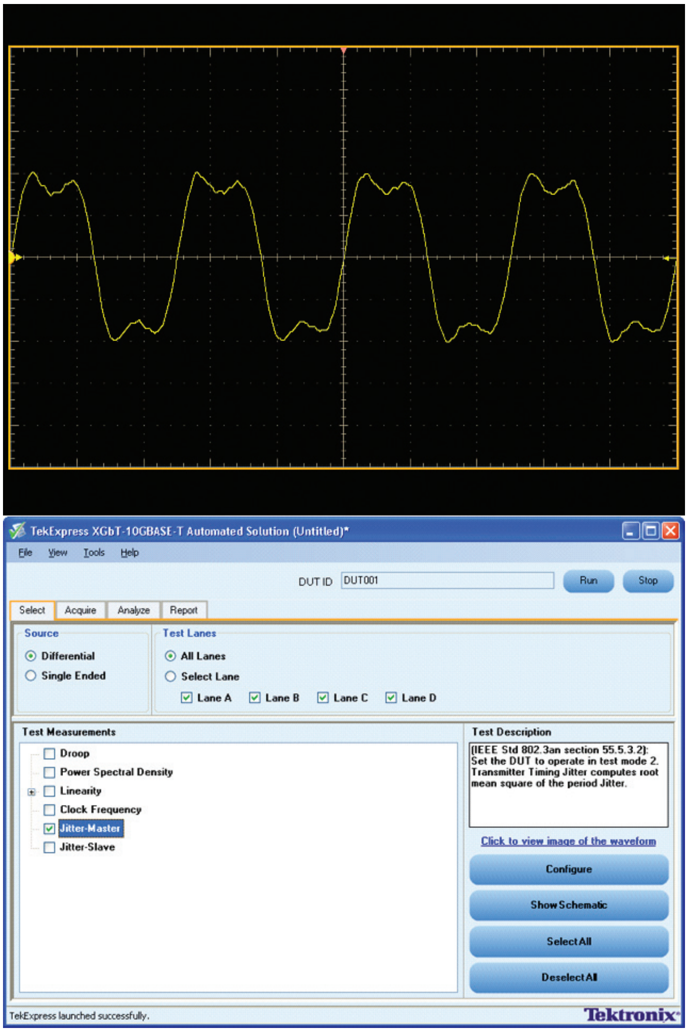


Figure 9. Transmit clock frequency - IEEE 802.3an-2006 Subclause 55.5.3.5.

Transmit clock frequency - IEEE 802.3an-2006 Subclause 55.5.3.5

Purpose: To verify that the frequency of the Transmit Clock is within the conformance limits.

IEEE Std 802.3an, clause 55.5.3.5 states that all 10GBASE-T devices must have a quinary symbol transmission rate of 800.00 MHz ± 50ppm while operating in Master timing mode. The reference clock used in this test is the one obtained in test 55.5.3.3, Transmitter Timing Jitter. The resulting frequency of the DUT transmit clock shall be 800 MHz ± 50 PPM. Configure the DUT for Test Mode 2 operation.

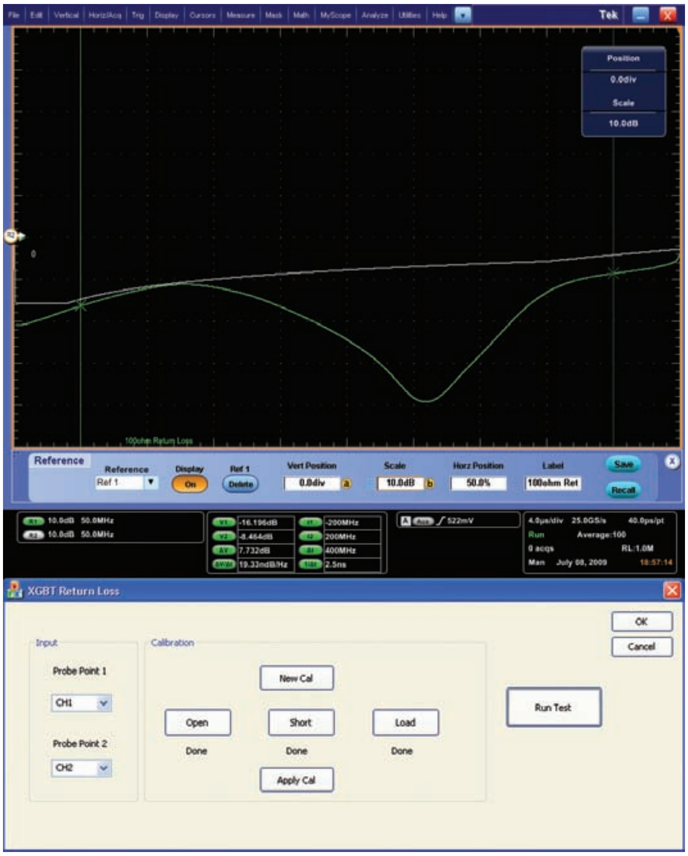


Figure 10. MDI Return Loss*1 - IEEE 802.3an-2006 Subclause 55.8.2.1.

MDI Return Loss[*1] - IEEE 802.3an-2006 Subclause 55.8.2.1

The return loss test provides an indication of the performance of the transmission system. The device is set to test mode 5.

Return loss is a measure of the signal power that is reflected due to the impedance mismatch.

The MDI on a 10GBASE-T device compliant with the IEEE 802.3an standard shall ideally have a differential impedance of 100Ω. Any difference between the impedance of the MDI and the impedance of the connector and cable results in reflections of the transmitted signals. Because the impedances can never be precisely 100Ω, and because the termination impedance varies with frequency, some limited amount of reflections must be allowed.

Return loss is a measure of the signal power that is reflected due to the impedance mismatch. This return loss must be maintained when connected to cabling with a characteristic impedance of 100Ω, and while transmitting data or control symbols.

802.3an specifies that the return loss measured at each MDI shall be at least 16 dB from 1.0 to 40 MHz, at least 16 – 10*log10(f/40) dB from 40 to 400 MHz, and at least 6 – 30*log10(f/400) from 400 to 500 MHz.

[*1] Get in touch with your local Tektronix sales representative for more information (Tektronix can share a utility that performs RL). For RL measurement in addition to DPO scope customers will require AWG7K/B (Minimum 5 G Samples/Sec) & 2 # P6330 (Same probe is used for ET3 based RL).

Tektronix and Ethernet Test Support

Tektronix provides a broad set of tools for Ethernet testing support across many different variants of the technology (data rate and media type).

Optical Ethernet:

The modular DSA8200 Series Sampling Oscilloscope mainframe provides support for 10GBE-SR up to 100 GbE with Acquisition module slots featuring optical front ends and selective receiver filtering. For clock recovery the 80A07 is recommended for clocks with speeds up to 12.5 Gb/s.

Electrical Ethernet:

The broad range of DPO7000 and DPO/DSA70000 Series Oscilloscopes are suited for electrical verification of copper Ethernet standards from the legacy 10BASE-T to the emerging 10GBASE-T standard.

Ethernet Cable:

The modular DSA8200 Series Sampling Oscilloscope mainframe provides support for Time Domain Reflectometry capability and fully integrated IConnect software for evaluating impedance effects and discontinuities for electrical Ethernet cables and connectors.

Conclusion

10GBASE-T Ethernet introduces new challenges for design and test. Despite numerous improvements in the UTP cable, every “trick in the book” of signal processing needs to be employed to achieve 10 Gb/s over 100 m of CAT-6a cable. To meet some of the challenges the 802.3an-2006 standard utilizes various techniques such as self-synchronizing scrambler, DSQ 128 coding, low density parity check, and more. Testing using XGbT 10GBASE-T Automated Compliance Software running on a Tektronix DPO/DSA70000 Series Oscilloscope delivers proper and optimal electronic testing for the validation of 10GBASE-T designs.

Additional information on Ethernet testing support:

www.tektronix.com/ethernet provides information on the latest Tektronix tool set for analog validation, compliance test, and device characterization, as well as additional testing resources such as webinars and application notes.

http://www.ieee802.org/3/10GBT/public/jan03/

www.ethernetalliance.org

IEEE 802.3an-2006

UNH-IOL document - 10GBASE-T_PMA_Electrical_v1.0.pdf

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