An Overview of the Electrical Validation of 10BASE-T, 100BASE-TX, and 1000BASE-T Devices

Application Note

The number of devices that come with a built-in network interface card has risen steadily and will continue to rise as more and more digital entertainment devices with networking capabilities are designed and sold. Devices with network interface ports now range from personal computers to closed-circuit cameras. This is a far cry from the day when a 10-Mbit/s port could be found only on high-end servers and networking equipment.

The technology used in these ports, commonly known as "LAN" or "NIC" ports, is usually one of the 10BASE-T, 100BASE-TX, and 1000BASE-T standards or a combination of them. These standards transmit 10, 100 or 1000 Mbit/s over UTP cable with an 8-pin RJ-45 connector. In this article, we will take a quick look at the electrical signals used in these technologies and how they can be probed for quick test and validation. This exploration will be useful for engineers involved in the electrical validation of the 10BASE-T, 100BASE-TX, and 1000BASE-T implementations in their devices.

10BASE-T

The long-lived 10BASE-T standard has been around since 1990 and is showing no signs of going away, even though it is considered obsolete by many. It provides 10-Mbit/s data transmission over two pairs of a Category 3 or 5 cable, one pair for transmit and the other for receive. The other two pairs of the cable are unused.

100BASE-TX

100BASE-TX is the most widely used version of 100-Mbit/s Ethernet (also known as fast Ethernet) over UTP cable. It uses the same pairs as 10BASE-T for transmit and receive but requires Category 5 or better cable.

1000BASE-T

1000BASE-T is the most common form of 1000-Mbit/s Ethernet (also known as Gigabit Ethernet) over UTP cable. It uses all four pairs of the UTP cable for both transmit and receive and requires Category 5e or better cable.

Figure 1 and Table 1 below describe the pin assignment of the 8-pin RJ-45 plug as used in a straight-through configuration.
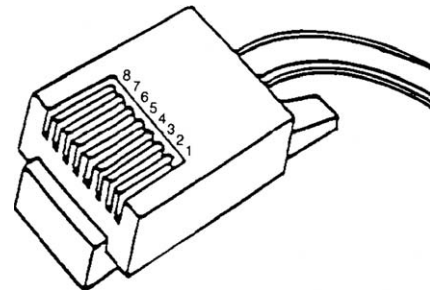

Figure 1. The 8-pin RJ-45 plug, also known as the 8P8C connector.

Pin	10BASE-T / 100BASE-TX	1000BASE-T
1	TD+	BI_DA+
2	TD–	BI_DA–
3	RD+	BI_DB+
4	Unused	BI_DC+
5	Unused	BI_DC–
6	RD–	BI_DB–
7	Unused	BI_DD+
8	Unused	BI_DD–

Table 1. The pin assignment for 10BASE-T, 100BASE-TX, and 1000BASE-T on the 8-pin RJ-45 plug in a straight-through configuration. TD/RD stands for transmit data/receive data. BI_D*x* stands for bi-directional pair *x*.

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Probing and Testing 10BASE-T Signals

10BASE-T transmits a differential signal, and the most straightforward method to probe the signals is with the TD+ and TD– pins connected to a 100 Ω resistive load as shown in Figure 2a. In addition to the 100 Ω resistive load, the standard specifies two additional loads to be used for testing. These two additional loads are illustrated in Figure 3. Apart from the direct connection from the TD

circuit to the load, the standard also describes the use of a "twisted-pair model" (also known as TPM in short). The TPM is an equivalent circuit that models the distortion introduced by a simplex link segment, and is made up of 4 segments of RLC circuitry not shown here. Tests for some of the 10BASE-T parameters are done iteratively with and without the TPM and on loads 1 and 2 including the

100 Ω resistive load. This makes for a lot of tests!

Let us take a look at the 10BASE-T waveforms. There are typically four different types of waveforms that need to be used for testing. All the waveforms in this article will be based on the circuit in Figure 2a with a 100 Ω resistive load unless otherwise mentioned.
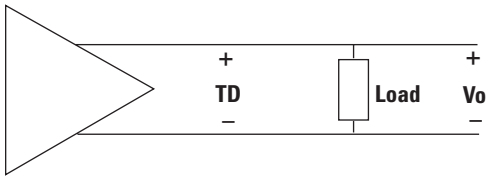

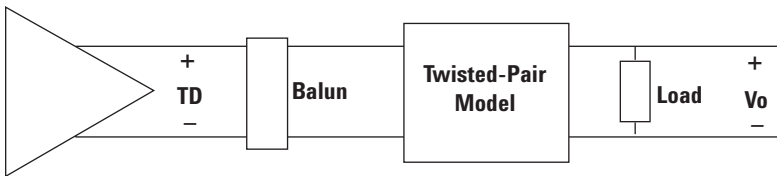Figure 2a. The 10BASE-T TD circuit directly connected to the load. The output voltage Vo is measured across the load.

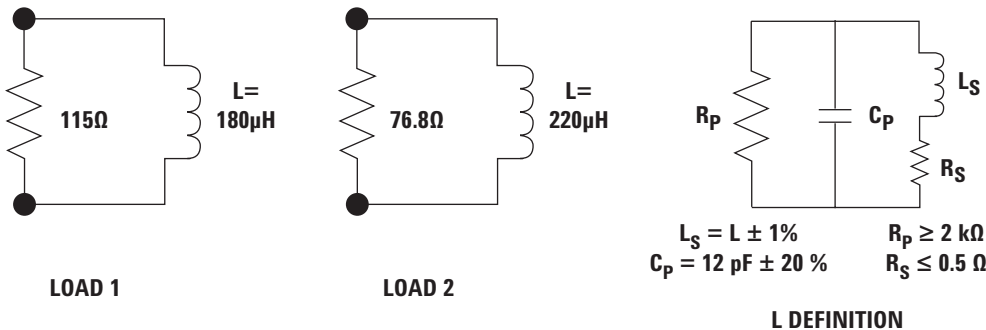Figure 2b. The 10BASE-T TD circuit connected to the load through the twisted-pair model (TPM).

LOAD 1   LOAD 2   L DEFINITION

Figure 3. Loads 1 and 2, which are used to test 10BASE-T.

Probing and Testing 10BASE-T Signals (continued)

First is the LTP or link test pulse, also known as the NLP or normal link pulse. The LTP is the first signal transferred by the 10BASE-T transmitter and is used to indicate the presence of an active transmitter. If there is an active device at the end of the link, it responds with its own LTP. The LTP is also used in bursts to form data words where device capability data is exchanged during auto-negotiation. In all cases, the LTP has to fit within a defined template with all combinations of loads with and without the twisted-pair model.
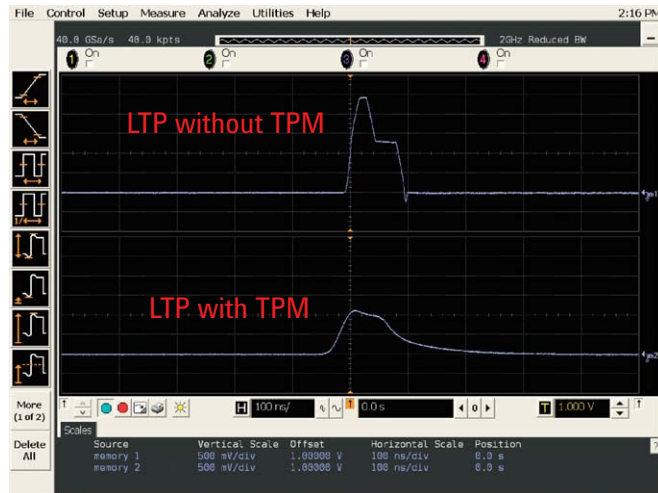

**Figure 4. The link test pulse (LTP) waveform with and without the twisted-pair model.**

Figure 5. LTP signal with TPM in the LTP template.

Probing and Testing 10BASE-T Signals (continued)

The next signal of interest is the TP_IDL signal. 10BASE-T data is transmitted in Manchester-encoded (transition indicates logical "1") data packets with a period of idle in between known as the interframe gap. The TP_IDL signal indicates the start of the idle period, and is therefore found at the end of each data packet. As with the LTP, the TP_IDL waveform also has to fit within a defined template with all combinations of loads with and without the twisted-pair model.
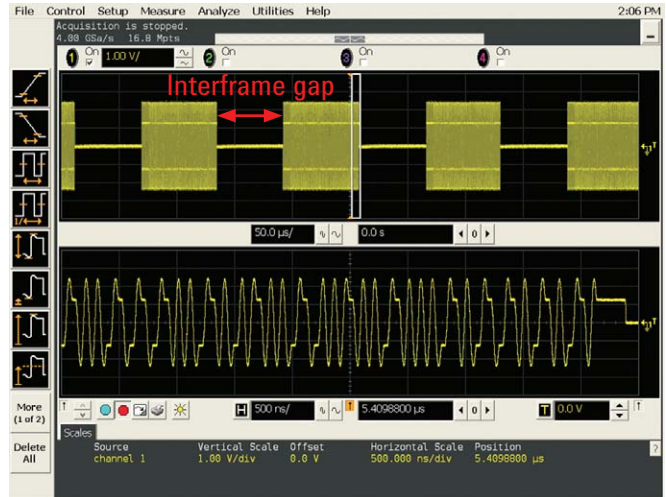
Figure 6. Manchester-encoded random data packets. The waveform displayed in the lower half of the screen is the zoomed-in area contained in the white box on the waveform in the upper half.

Figure 7. The TP_IDL is a positive-going pulse with a width of 300 ns or 350 ns depending on whether the last bit was one or zero respectively.

Figure 8. The TP_IDL template test.

The signaling rate for 10BASE-T is nominally 10 MHz. An all-1's Manchester-encoded signal will result in a 10-MHz waveform. This all-1's waveform is used to test that all harmonics measured on the transmitting circuit are at least 27 dB below the fundamental. This is easily achieved, as most modern digitizing oscilloscopes come with an FFT function. Through the use of FFTs made with the Hanning window function for frequency accuracy, it is easy to measure the magnitude of the spectrum at 10 MHz and its harmonics.

Apart from the template tests and the test for harmonic content, the other parameters that can be tested are the peak differential output voltage and common-mode voltage. These tests are performed with random data signals, as shown in Figure 6, and are relatively straightforward measurements.
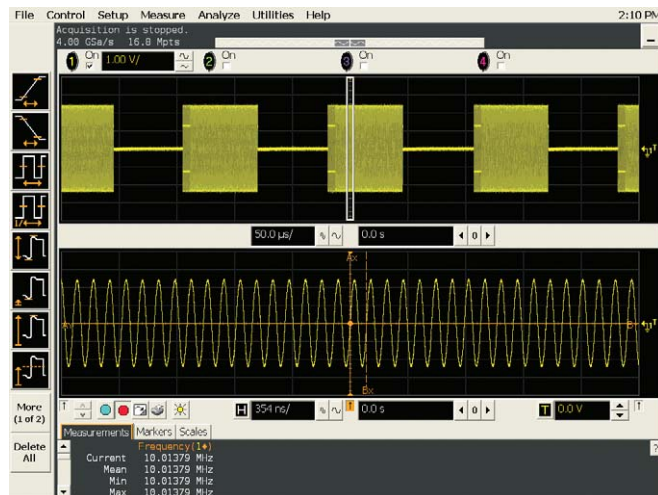

Figure 9. All-1's Manchester-encoded signal.

Figure 10. The oscilloscope display is divided into two, with the trace on the upper portion displaying the all-'1's Manchester-encoded signal. The trace on the lower portion uses the oscilloscope FFT function to measure harmonic content of the all-1's Manchester-encoded signal. This example shows a marker at the fundamental frequency of 10 MHz and another marker on the third harmonic (30 MHz). The magnitude of the third harmonic shown here is –28.45 dB from the fundamental.

Testing 100BASE-TX

100BASE-TX uses a line encoding scheme known as MLT-3 where the data is alternated through three voltage levels with a transition indicating a logical 1. The MLT-3 line coding enables the use of less bandwidth than would be required by a different coding scheme, such as NRZ, for the same data rate. 100BASE-TX is tested using an MLT-3 coded idle pattern. On most devices, setting the speed setting to 100 Mbit/s mode will automatically cause the device to output an idle pattern, part of which is shown in Figure 11. This same pattern is used for all 100BASE-TX tests.

The 100BASE-TX standard provides the use of an eye pattern template that can be used to perform a quick check on the output of a 100BASE-TX transmitter. Note that the use of the eye template should not replace thorough testing of 100BASE-TX parameters, but it can provide a reasonably good indication of the performance of a particular transmitter.

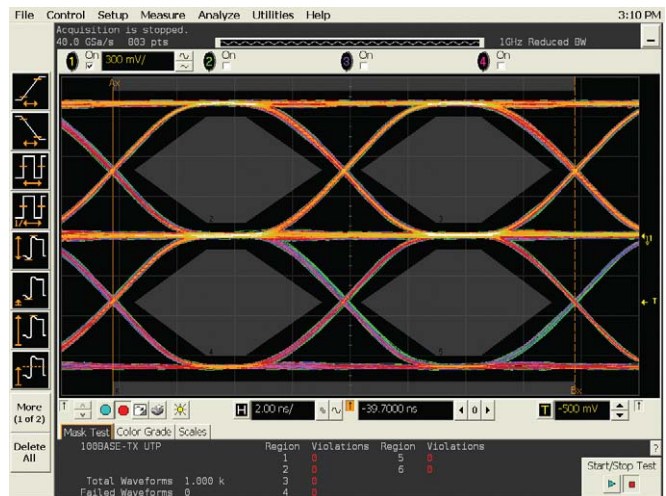**Figure 11. The MLT-3 coded idle pattern from a 100BASE-TX transmitter.**

Figure 12. The eye pattern template of a 100BASE-TX signal. The oscilloscope used to create the eye-pattern is synchronized to the recovered clock from the transmit waveform.

Testing 1000BASE-T

1000BASE-T transmits data over all four pairs of the twisted-pair and uses a five-level pulse amplitude modulation called PAM5 for data transmission. Performing tests on normal data transmission similar to 10BASE-T or 100BASE-TX is non-trivial, thus the standard defines the use of four different test modes for testing. These are named test modes 1 – 4 and are set by writing to bits 13 to 15 of the 1000BASE-T control register (register 9.13:15). Tests are performed over all four pairs of the transmitter.

Test Mode 1 causes the transmitter to send out all five signal levels of the PAM5 coding, which are the "+2", "–2", "+1," "–1" symbols alternating with 127 "0" symbols. This is then followed by long strings (128) of the "+2" and "–2" symbols repeated twice, and ends with 1024 "0" symbols. Various points in the waveform are then labeled from A to M (I is skipped) to mark points of interest for testing. Points A, B, C, and D corresponds to the "+2," "–2," "+1," and "–1" symbols respectively.

Three tests are done using Test Mode 1. First, the peak voltages at points A, B, C, and D are measured. The voltages at points A and B are also compared to ensure their amplitudes are within 1%. These measurements are relatively straightforward to make, and it involves zooming in to the point of interest and making the measurement.
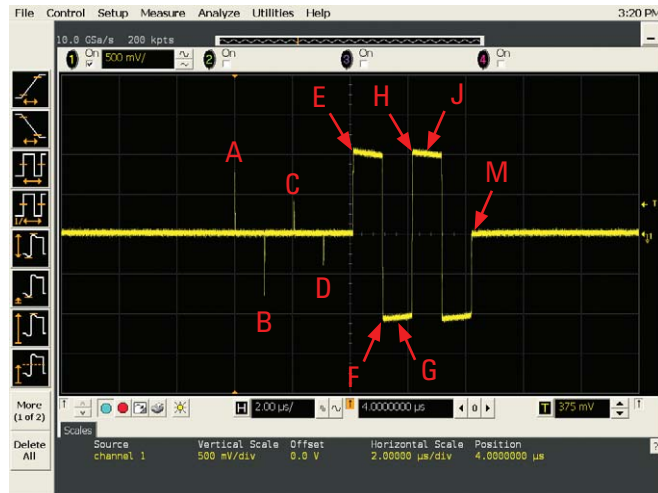

Figure 13. One cycle of a Test Mode 1 waveform with the test points A to M labeled.

Testing 1000BASE-T (continued)

The next tests are the template tests. Points A, B, C, D, F, and H have to fit in defined templates after going through a 2-MHz high-pass filter and being normalized according to specific rules described in sub-clause 40.6.1.2.3 of IEEE Standard 802.3-2005. These steps can be achieved using currently available digitizing oscilloscopes as shown in Figures 14a, 14b and 14c below, using the template measurement for point A as an example.

Apart from the template tests, there is also a droop test on the long strings of the "+2" and "–2" symbols. The voltage droop is measured from point F (minimum point at the start of "–2" symbol string) to point G (500 ns after point F) as well as from point H (maximum point of the waveform as indicated in Figure 3) to J (500 ns after point H).
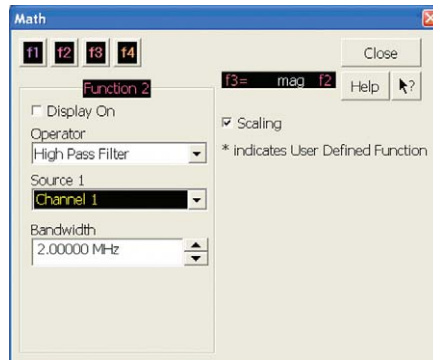
Figure 14a. The digitizing oscilloscope in this example allows the use of functions to be performed on waveforms. In this illustration, a high-pass filter with its lower cutoff at 2 MHz is applied on the Channel 1 source using Function 2.
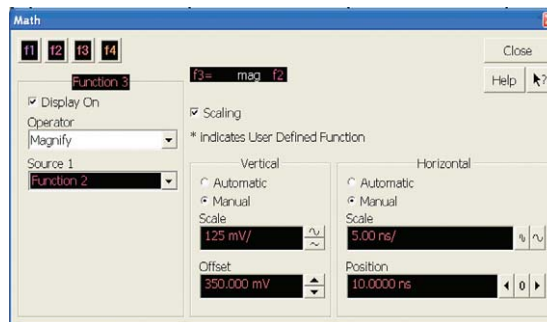

Figure 14b. Function 3 then uses a magnify function to normalize the filtered waveform from Function 2. The point A waveform is normalized by dividing by the peak voltage value of the waveform at A.

Figure 14c. The filtered and normalized point A waveform is then aligned to best fit to the template.

Testing 1000BASE-T (continued)

Next, we will take a look at test modes 2 and 3. These test signals consist of alternating "+2" and "–2" symbols timed to a 125 MHz timing clock called the TX_TCLK. Test Modes 2 and 3 differ in the timing source used. Test Mode 2 is called Master mode, and uses the device's own transmit clock, while Test Mode 3 is called Slave mode and uses a recovered clock from data transmitted by a link partner in Master mode. To be able to test the jitter of a 1000BASE-T device, the TX_TCLK of the device should be available for probing. The data sheet of the 1000BASE-T device should describe which pins should be probed to access the TX_TCLK. The waveforms for test modes 2 and 3 are essentially the same; an example waveform and a TX_TCLK is displayed in Figure 13. Jitter testing will not be covered in detail here as it is beyond the scope of this article.
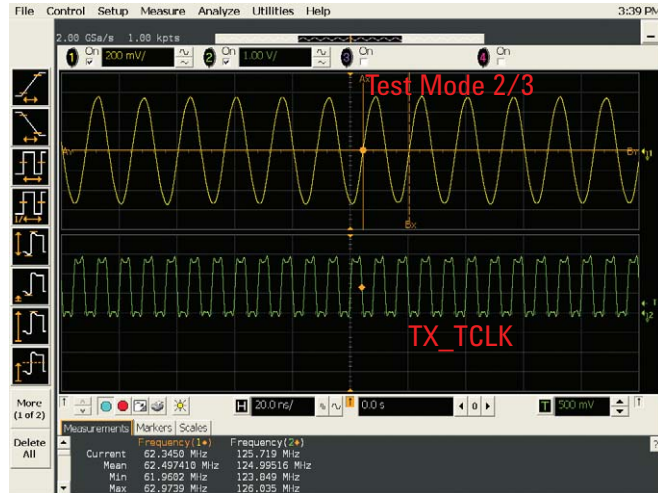
Figure 15. Test mode 2/3 waveform along with a 125MHz TX_TCLK.

Testing 1000BASE-T (continued)

The last test mode that we will look at is Test Mode 4. In Test Mode 4, the device outputs a 2047 symbol pseudo random bit pattern that is PAM5 encoded and then further filtered through a partial response filter. The resulting output from the filter is a 17-level signal, which can be seen in Figure 14. The Test Mode 4 waveform gives an idea of what the waveform from an actively transmitting 1000BASE-T device looks like. The Test Mode 4 output is used as the source to measure peak transmitter distortion.

The distortion measurement is not a straightforward oscilloscope measurement; it requires the use of post-processing to calculate distortion. Sample MATLAB® code is provided in the standard as a guidance to calculate distortion. In simple terms, what the code does is to sample each of the 2047 symbols at an arbitrary phase clocked from the TX_TCLK. The code then examines each sample for distortion and reports the highest value as the peak distortion. This usually involves obtaining a large record containing more than a few cycles of the Test Mode 4 waveform. This waveform record is then transferred to a personal computer and processed based on the guidance given in the MATLAB code.

As in 10BASE-T where the standard calls for some tests to be run with a twisted-pair model, the 1000BASE-T standard also calls for the Test Mode 1 and Test Mode 4 tests to be run in the presence of a disturbing signal. The disturbing signal is defined as a sine wave generator that simulates the potential interfering effect of another 1000BASE-T transmitter. We will not cover testing with disturbing signal in detail in this article.

Figure 16. The Test Mode 4 waveform.

Return loss testing

Return loss is a measurement of the sum of the reflected energy coming back from the receiving device to the transmitting device. Return loss is defined in the standards for 10BASE-T, 100BASE-TX, and 1000BASE-T. It is especially important for 1000BASE-T devices as these devices use bi-directional signaling. These means that the same pins which transmit data also receives data. If the receiving device has bad return loss, the information originating from the transmit side will be reflected back, causing problems for the transmit side as it is also acts as a receiver, listening for data from the transmitter at the other end. Therefore return loss testing is important to ensure interoperability with other devices.

Return loss testing is performed using a vector network analyzer. The N5395B or N5395C Ethernet electrical probing fixture can be used to facilitate the return loss measurement. As the signals from the Ethernet device are differential, a balun transformer on the fixture performs the differential to single-ended impedance conversion to the network analyzer input. The N5395B or N5395C fixture also provides a return loss calibration fixture with RJ-45 short, open, and load connections to calibrate the vector network analyzer.

The return loss can be measured on a single-port of the vector network analyzer using a forward reflection or S11 measurement in log magnitude. As this measurement is made in 50 Ω through a balun, it has to be conversion mathematically to its equivalent in 100 ± 15 Ω. Therefore return loss is calculated at 85 Ω, 100 Ω, and 115 Ω (111 Ω additionally for 10BASE-T).

To perform the conversion, we use the following equations:
Return Loss in dB, $RL_{dB} = 20 \log_{10} |\Gamma_0|$

Where Γ_0 is the array of complex reflection coefficient values (vs frequency) of the measurement made on the VNA and is represented in terms of impedance by

$$\Gamma_0 = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

Z_{in} is the impedance of the DUT which is also a complex array (vs frequency), and Z_0 is the standard reference impedance at which the measurement was made (real number).

Since the measurement was made on the vector network analyzer at the standard reference of 50Ω, but first going through a 2:1 conversion through the balun, $Z_0 = 2*50 = 100$.

Solving for Z_{in},

$$Z_{in} = Z_0 \, \frac{1 + \Gamma_0}{1 - \Gamma_0}$$

From Zin, the reflection coefficients for the different impedances can be calculated.

$$\Gamma_{85\Omega} = \frac{Z_{in} - 85}{Z_{in} + 85}$$

$$\Gamma_{100\Omega} = \frac{Z_{in} - 100}{Z_{in} + 100}$$

$$\Gamma_{115\Omega} = \frac{Z_{in} - 115}{Z_{in} + 115}$$

And the resulting return loss in dB can be obtained by the following:

$RL_{85\Omega} = 20 \log_{10} |\Gamma_{85\Omega}|$
$RL_{100\Omega} = 20 \log_{10} |\Gamma_{100\Omega}|$
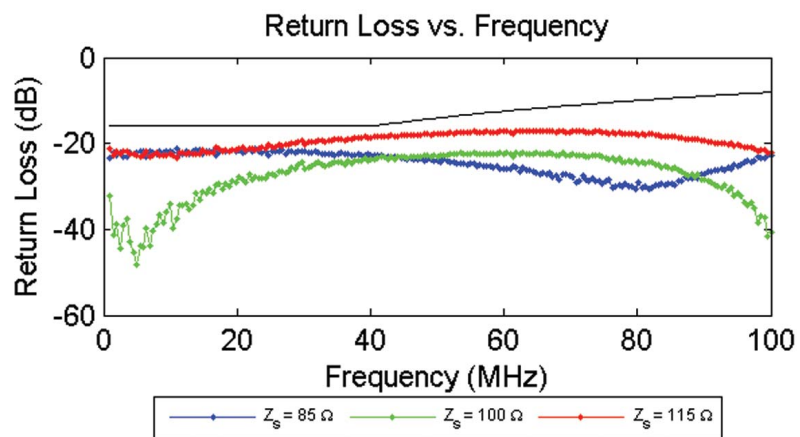$RL_{115\Omega} = 20 \log_{10} |\Gamma_{115\Omega}|$

Figure 17. Return loss vs frequency plot of a 1000BASE-T device

Conclusion

You now have an overview of the how the electrical validation of the popular 10BASE-T, 100BASE-TX, and 1000BASE-T is done. The signals used in the transmission of Ethernet signals get more complex as the data rate increases exponentially from 10 to 1000 Mbits/s. This trend will continue as designers try to transfer more data over the bandwidth-limited UTP cable using more complicated modulation schemes.

The quality and signal integrity of your measurement tools play an important role in ensuring that you have the best representation of the signals you are measuring. Most of the measurements described here can be made manually on a modern digitizing real-time oscilloscope. The signals used in these illustrations were from an off-the-shelf network interface card and captured using an Agilent 80000 Series

oscilloscope with an active differential probe. An Agilent N5395B or N5395C Ethernet electrical probing fixture was used to provide the probing circuits shown in Figures 2 and 3. There is also an automated test application available that can be used in conjunction with the N5395B or N5395C fixture. For more information regarding tools for Ethernet validation, visit **www.agilent.com/find/n5392a**.

Related literature

Publication title	Publication type	Publication number
N5392A Ethernet Electrical Performance Validation and Compliance Software for Infiniium Oscilloscopes	Data Sheet	5989-1527EN
Infiniium DSO80000B Series Oscilloscopes and InfiniiMax Series Probes	Data Sheet	5989-4606EN
Infiniium 90000 Series Oscilloscopes	Data Sheet	5989-7819EN

Product Web site

For the most up-to-date and complete application and product information, please visit our product Web site at:
www.agilent.com/find/n5392a
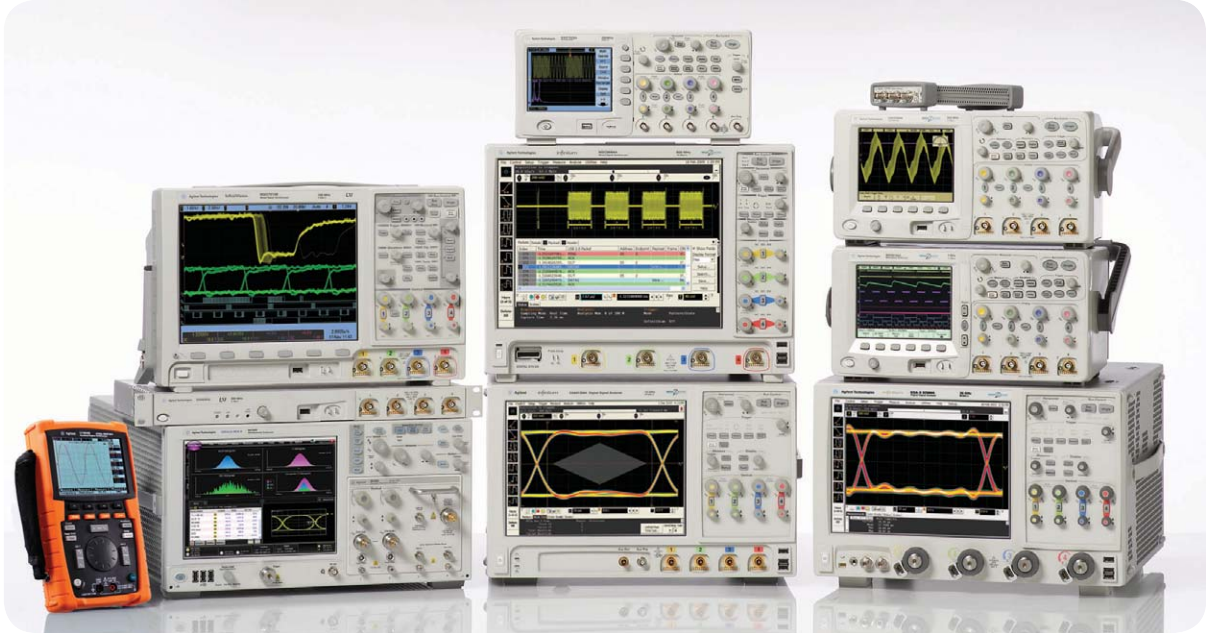
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