

LINK TESTING IN THE TIME DOMAIN AND PERFORMANCE ADVANTAGES OVER SWEEPED FREQUENCY MEASUREMENTS

J.S. Bottman, H. Koeman

Fluke Corporation, Everett, WA, USA

ABSTRACT

Time Domain Response Measurement methods for twisted pair cable transmission characteristics offer significant advantages over traditional swept frequency methods. These advantages include: substantial increase in measurement speed, greatly enhanced diagnostic capability and state-of-the-art accuracy, even when user patch cords are used to connect the link to equipment.

The time samples are used to calculate the equivalent frequency response using digital signal processing and Fast Fourier Transforms. The DSP methods include estimating the unwanted Near End Crosstalk (NEXT) contributions from the local and remote instrument connectors and excluding this response from the NEXT performance of the link that is reported.

The basic measurement and practical performance results concepts are described.

INTRODUCTION

Swept frequency methods are commonly used to specify performance of components and links for data communication [1-3]. They are also commonly used in specific applications as well as field test equipment.

The pulse response approach to LAN cable testing results in a unified, uniquely capable

measurement system. Time domain measurements include Time Domain Reflectometry, Time Domain Crosstalk, and cable impedance estimation. The frequency domain parameters of attenuation and NEXT are obtained by Fourier analysis of the steady state pulse response, and are exactly equivalent to results obtained through the traditional swept frequency approach. The pulse based approach simultaneously applies a large number of harmonically related test frequencies to the cable under test, and analyzes the resulting pulse response with the Fast Fourier Transform algorithm to find the amplitude and phase of each harmonic. By comparing these results with calibration data obtained under a known reference condition, transfer functions are calculated. This approach is inherently faster and more efficient than sequential application and measurement of the large number of test frequencies required for adequate cable verification.

Both phase and amplitude information are available through pulse based analysis. This makes measurement of complex impedance, and thus return loss, possible. Return loss cannot be measured with a scalar swept frequency test system.

In the formal definition of a link the connection to the equipment at both ends of the interconnect cabling is excluded, although physically those end connections are part of the patch cord [1]. The reason is

that the electrical performance of data communication equipment is tested at the cable side of the plug mating with the instrument jack and there should be no double accounting for the transmission performance by connections. International standards [4] define the link slightly different: they exclude also the cordage of the patch cord at both ends, but include the plug making connection to the fixed wiring.

This presents serious problems for test equipment designers, who have to perform a measurement through an instrument jack/mating plug, but somehow have to suppress measurement errors resulting from this component. This is a very serious problem during the measurement of Near End Crosstalk (NEXT), the most important parameter affecting high frequency transmission. NEXT is also the parameter most affected by workmanship errors, so it is important to test NEXT in the field.

Connecting hardware is a point source of NEXT, and practically cause serious limitations of link performance. NEXT contributions in cable are distributed in nature and tend to be far less harmful. Figure 1 shows a typical time domain response as displayed on a tester that illustrates this.

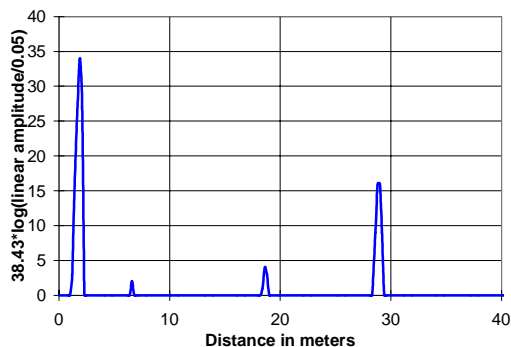


Figure 1: Typical time domain response of a link showing NEXT contributions from cable and connecting hardware.

The link committee of the Telecommunications Industries Association (TIA) recognized that tighter requirements were appropriate for the horizontal cabling portion of a link and defined a “basic link” configuration [2]. The equipment cord, delivered with the field tester is used in this configuration. The solution to overcoming the impact of the instrument connector by several manufacturers of field test equipment has been to use a low NEXT connector with a special equipment cord with a mating plug at one end and a standard modular plug at the other end. This overcomes the measurement error by NEXT introduced at the connection to the field tester and its remote unit. This solution is suitable for the basic link configuration (see figure 2), which is intended to represent the fixed horizontal wiring portion of the link.

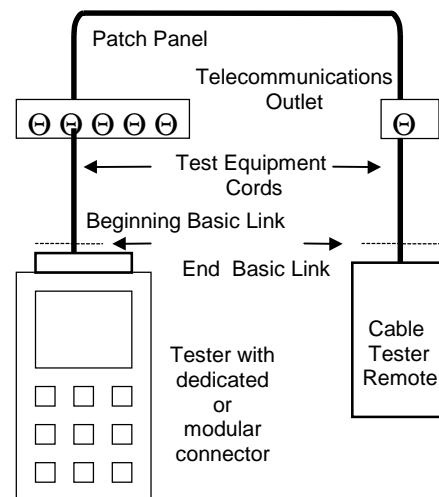


Figure 2: Basic Link configuration per TSB-67

This solution is not available for the channel configuration (see figure 3), where provisions for mating with a modular plug are needed. The channel is intended to represent the end-to-end connection including the user patch cords. In this case the end-plug, which is typically of the modular variety, must be accommodated by the tester.

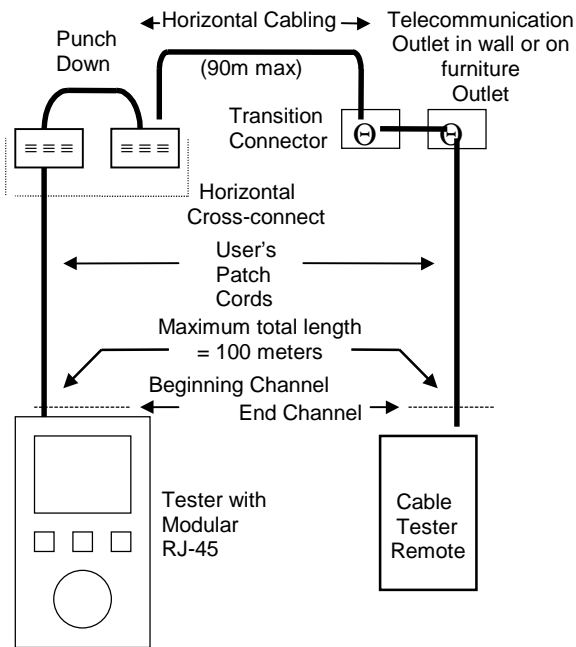


Figure 3 Definition of “channel” type link.

The time domain measurement approach provides means to selectively eliminate portions of the time response associated with the local and remote connector. Principles of operation and practical performance aspects for the NEXT measurement of a link equipped with modular end connectors are described.

PULSE RESPONSE MEASUREMENT SYSTEM

A pulse response digitizer generates a data record for the cable under test that provides input for subsequent signal processing. Sample rate and record length are determined by requirements of the test modes. For example, frequency measurement to 100MHz requires a sample rate of at least 200Ms/s, and must be much higher to allow for practical anti-alias filtering. Thus 500Ms/s was chosen as the fastest sample rate. Data record length is determined by NEXT frequency spacing. A 4096 point record length was chosen to meet

the 150kHz requirement in TSB-67. The internal frequency step size is 0.122MHz. Values at 100kHz increments are obtained by linear interpolation. The NEXT and TDR functions require a number of pulse widths to cover the dynamic range with sufficient signal-to-noise ratio. Table 1 summarizes the capabilities of the digitizer.

Parameter	Values
Sample Rate	62.5, 125, 250, 500 Ms/s
Record Length	4.096 to 16.384 μ s
Pulse width	5, 16, 64, 240 ns

Table 1: Digitizer capabilities

Sequential sampling is used to obtain effective high sample rates with a much lower real time sampling rate of 3.91Ms/s. A data record is built over a large number of excitation pulses by measuring only a subset of the total record with each pulse, and storing the result in the appropriate indexed locations in acquisition memory. Averaging reduces the noise floor and is achieved by summing A/D output data into acquisition memory on the fly. For example, each data point in a NEXT record is the sum of 128 A/D converter readings.

Computer modeling of the measurement system revealed two major sources of transfer function error: amplitude error, such as A/D quantization and non-linearity, and sample time errors. The A/D converter has 10 bits of resolution. Variable DC offset injection over a 7 bit range is used during data record acquisition in order to smooth the quantization curve, thereby increasing linearity and resolution. This technique provides adequate amplitude accuracy. Sample time uniformity is of critical importance for accurate transfer function measurement, and timing circuits were optimized for adequate uniformity.

NEXT MEASUREMENT

Category 5 LAN cabling is tested for NEXT over a 1-100MHz frequency range. The pass/fail test limit is approximately the following function of frequency:

$$NEXT_{limit} = 27 - 15 * \log(f / 100)$$

where f is the frequency in MHz. Thus a measurement system with constant signal power and noise floor will have 30dB worse signal-to-noise ratio at 1MHz than at 100MHz when measuring near the limit.

Signal power is increased at lower frequencies during the NEXT measurement by using three pulse widths, corresponding to three frequency bands as shown in table 2.

Freq. Range	Pulse Width	1st Null Power Spectrum.
1-10MHz	64ns	15.6MHz
1-40MHz	16ns	62.5MHz
40-100MHz	5ns	200MHz

Table 2: Pulse width selection

This technique results in a signal power spectrum that maintains approximately uniform signal-to-noise ratio when measuring close to the test limit. A NEXT noise floor of about 100dB is achieved in the 1-10MHz range, providing about 40dB of margin at the 60dB test limit at 1MHz. Note that the measurement accuracy is most critical in the region close to the pass/fail test limit.

NEAR END CONNECTOR COMPENSATION

The link definition requires exclusion of crosstalk from the test instrument. Most often the modular connector is used. Unfortunately, its physical design results in a high, unpredictable crosstalk (e.g., 40dB typical at 100MHz). Fortunately, the pulse

response based measurement approach allows exclusion of most of the NEXT from the instrument connector.

The technique essentially constructs an estimate of the the near end connector pulse response from the measured pulse response. The measured response includes crosstalk from the near end connector as well as the link under test.

An example of the 5ns response of the near end connector (nec) NEXT and the total link NEXT response is shown in figure 4. During calibration the beginning of the connector response is identified. During the measurement of the link, the near end connector pulse response is obtained from the 10ns time interval that follows the defined start of the connector response. Other adjustments are made for the long term response contribution from the connector. The connector estimate is then effectively subtracted from the uncompensated NEXT that is calculated.

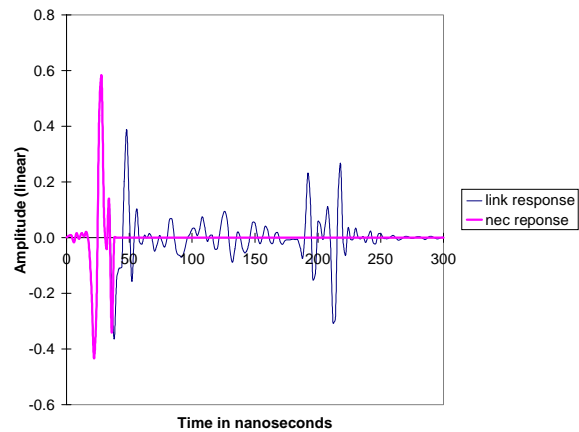


Figure 4: 5ns Response of near end connector and 15m basic link.

Patents related to the measurement principles, which were described in this article have been applied for.

MEASUREMENT PERFORMANCE

The performance of a time domain measurement based field tester is illustrated with key performance parameters related to the measurement of NEXT. It includes consideration of sources of error from excluded cable NEXT, and variations in local connector NEXT performance by modular connector.

Overall measurement performance relative to network analyzer measurements are shown as well.

Residual NEXT performance

The immediate benefit is rejection of the NEXT of the local connector. When terminated by just 100Ω, the residual NEXT improves from approx. 40dB to approx. 70dB at 100MHz. However, reflections and coupling inside the instrument jack/mating plug reduces this to approx. 60dB. See figure 5 for a typical result measured per TSB-67 guidelines.

As expected, the worst performance occurs with the 3,6-4,5 pair combination.

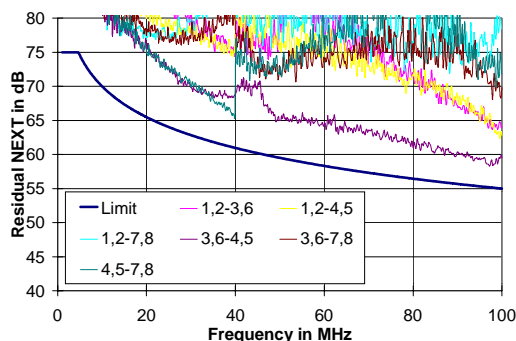


Figure 5: Residual NEXT of modular connector measured with DSP techniques.

Transition of sensitivity

While suppression of unwanted connector NEXT is achieved, some portion of NEXT from cable near the local instrument connector is lost as well. Figure 6 shows the sensitivity as a function of distance from the local connector for the NEXT at 100MHz.

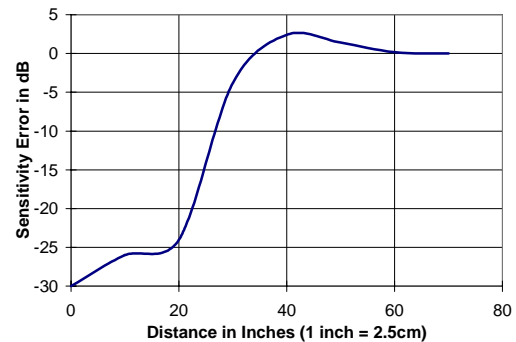


Figure 6: Sensitivity as a function of distance from the local connector at 100MHz

Note that the rejection of the connector NEXT is approximately 30dB. The sensitivity turns on rapidly between 50cm (20”) and 75cm (30”) from the equipment connector and is slightly overly sensitive at 1m (40”)..

Measurement Error Considerations

The error in the NEXT of the link is lack of NEXT from a portion of jacketed cable. This amount can be measured and calculated. For a short segment of cable, the result is

$$NEXT_{dB,length} = 10 * \log(K_N * f^2 * length)$$

where the length is expressed in meters and frequency f is in MHz. Constant K_N for nominally performing category 5 cable is $6*10^{-9}$. At 100MHz, the result is:

$$NEXT_{dB,1m} = -42.2dB$$

Since the NEXT in a cable is distributed in nature, the error caused at a nominally performing channel is given by:

$$E_{dB,1m} = -10 * \log(1 - K_N * f^2 * 10^{\frac{NEXT_{dB,nom}}{10}})$$

In this equation, $NEXT_{dB,nom}$ represents the nominal signal level, e.g., the test limit for a category 5 channel. At 100MHz the error is 0.13dB for a 1m long cable and insignificant relative to the overall 1.5dB accuracy objective.

Instead, the potential error contribution from a local connector NEXT is fixed in phase relative to the point of measurement and therefore can easily add worst case with the NEXT of the link to be measured. For a nominally performing category 5 connection, the error is 1.8dB @ 100MHz at the test limit for a channel.

In-situ measurement of local connector NEXT

Since the time record includes the response of the local connector, it is possible to determine the frequency domain equivalent of the amount that is excluded from the computation of the NEXT for the defined link. An example of the frequency response on a logarithmic frequency scale is shown in figure 7.

Note that the slope closely resembles 20dB/decade, as predicted for NEXT from connecting hardware; cable “slopes” at 15dB/decade. This result confirms that short segments of cable contribute very little error. Also note the dynamic range at low frequencies. In order to avoid passing any seriously damaged patch cord, if not already detected during other tests, the time domain

tester can issue warnings, if expected NEXT for the compensated amount is outside normal levels.

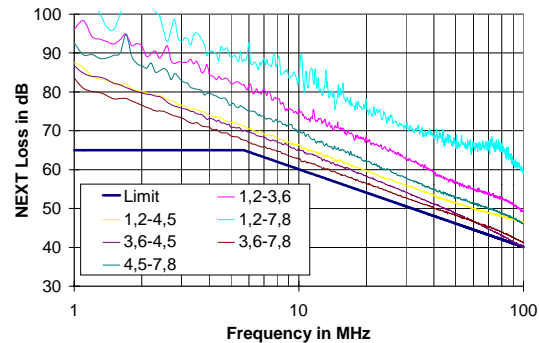


Figure 7: Local connector compensation amount as a function of frequency.

Not every plug inserted into a category 5 compliant modular jack results in a connection that complies with the category 5 requirements [1]. The explanation might be that the qualification procedure in [1] selects first a test plug and then verifies performance of the plug/jack combination. Instead, the jack of a field tester is always fixed and plugs of user patch cords vary.

Comparisons with network analyzer measurements

Reference [3] contains in Annex B information on how to properly make measurements so that results from field testers and network analyzers are directly comparable.

Sample results of comparison are reported on the very same basic link by several independent and very qualified parties, using laboratory equipment. All parties used 0322BF North Hills baluns, but different network analyzers. Along with these results, the response of a time domain measurement field tester is plotted. The links that were tested tended to have less favorable balance properties, and represent potentially worst

case quality links. The 3,6-4,5 pair combination examined as generally representing a worst case situation.

One will note that in some cases very good correlation exists between the independently obtained network analyzer results. It will be found that the agreement with the response of a field tester is as good. See figure 8. The fat line is the time domain tester; the thin lines represent the results of laboratory equipment. For some links, the level of agreement is superb.

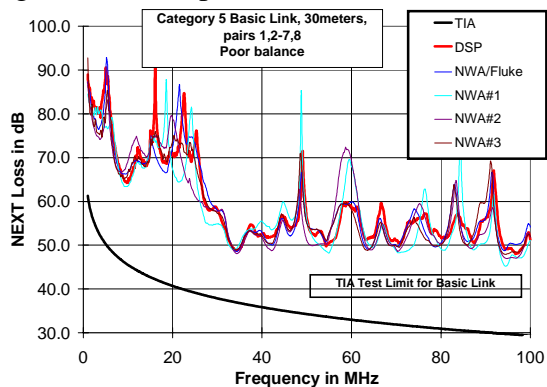


Figure 8: Comparison network analyzer responses vs. time domain tester, better correlation.

In other cases relatively poor correlation exists between independently obtained network analyzer results. In those cases, the agreement with the response of a field tester is not as good as well. See figure 9.

One may conclude that secondary link parameters affect the measurement accuracy. The current draft of [3] contains the initial error model and it has been agreed that it is satisfactory for an initial step. It will be subject of future research and will likely be enhanced in future issues of [3].

It is found also that in any case, the agreement between worst case NEXT margins is well within the measurement errors of the field tester and network

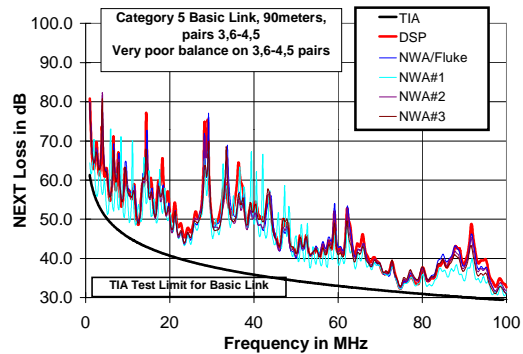


Figure 9: Comparison network analyzer responses vs. time domain tester, worse correlation.

analyzer. Table 3 shows typical results for three links. The first column contains information on the link. Good (longitudinal) balance is 40dB or better, Average balance is 30-35dB, Poor balance is <30dB. The Network Analyzer Result column (NWA) shows the worst case NEXT margin as

Link	Pairs	NWA (dB)	Delta #1 (dB)	Delta #2 (dB)	Tol. (dB)
Cat 5	1,2-3,6	3.9	+0.2	+0.4	2.5
30m	1,2-4,5	7.3	-0.8	-0.9	2.7
Ave	1,2-7,8	11.0	+1.4	+1.3	3.3
bal.	3,6-4,5	2.1	+0.1	-0.2	2.4
	3,6-7,8	9.2	+0.3	+0.1	3.0
	4,5-7,8	7.7	0.0	+0.1	2.8
Cat 5	1,2-3,6	14.8	-0.2	-0.3	4.2
60m	1,2-4,5	8.7	+0.6	+0.5	2.9
Good	1,2-7,8	12.4	+1.5	+1.0	3.7
bal.	3,6-4,5	7.7	+1.7	+1.5	2.8
	3,6-7,8	11.1	-0.9	-0.8	3.3
	4,5-7,8	7.7	+0.3	+0.2	2.8
Cat 5	1,2-3,6	3.1	-0.3	-0.2	2.5
90m	1,2-4,5	2.4	-0.4	-0.3	2.4
Poor	1,2-7,8	1.4	+0.9	+1.1	2.3
bal.	3,6-4,5	1.3	+0.2	+0.2	2.3
	3,6-7,8	5.2	+0.2	+0.3	2.6
	4,5-7,8	3.4	0.0	+0.1	2.5

Table 3: Comparisons of worst case margins by two time domain testers against network analyzer results.

measured by the network analyzer. The deviation of the worst case margin by two time domain testers is shown in the columns marked Delta #1 and Delta #2. The tolerance column (Tol) is the allowed difference computed guidelines of Annex B of [3].

Note that the observed differences are always less than approx. 60% of the tolerance that is allowed, even under relatively unfavorable conditions. Furthermore that the two different testers tend to be very consistent in their results. This is confirmed by the frequency plots which are virtually on top of each other.

CONCLUSIONS

The time domain measurement method has been shown to provide accurate NEXT measurements, even when modular connectors are used, since it includes the ability to electronically “cut off” unwanted responses. Integrated circuits that incorporate fast Fourier transform functions have made it practical to design a hand held instrument.

Also, the deviations from “ideal” network analyzer based test results are no worse than the variations observed between results obtained from different network analyzer based setups.

In addition to achieving the highest level of measurement accuracy, it can be shown that the time domain based tester meets the required performance for random noise, residual NEXT, output signal balance, common mode rejection, dynamic accuracy and return loss for Accuracy Level II performance for both a basic link and channel configuration. The results of these tests are not discussed in this paper.

Furthermore, the speed of the measurement is very high. Time domain responses provide excellent means to diagnose and locate transmission problems on the link.

REFERENCES

1. TIA standard TIA/EIA-568-A
2. ASTM standard ASTM D-4566-1994
3. TIA Telecommunications Service Bulletin (TSB) - 67.
4. ISO/IEC standard ISO/IEC IS-11801
5. IEC standard IEC 1156-1994

Jeff Bottman is a Senior Staff Engineer with Fluke. He has worked on a time domain cable tester since its inception. He designed the high speed measurement system and also specified the digital signal processing algorithms. Jeff holds a MSEE degree from Stanford University.

Henricus Koeman has a PhD degree from the University of Nymegen (The Netherlands) and is a Principal Engineer with Fluke. He is the Fluke representative to the TIA link committee.