55.7 Link segment characteristics

10GBASE-T is designed to operate over ISO/IEC 11801 Class E or Class F 4-pair balanced cabling that meets the additional requirements specified in this subclause. Each of the four pairs supports an effective data rate of 2500 Mb/s in each direction simultaneously. The term “link segment” used in this clause refers to four duplex channels. Specifications for a link segment apply equally to each of the four duplex channels. All implementations of the balanced cabling link segment specification shall be compatible at the MDI. It is recommended that the guidelines (proposed) in ANSI/TIA/EIA-TSB-155, ANSI/TIA/EIA-568-B.2-10 and ISO/IEC 11801 Edition 2.1 be considered before the installation of 10GBASE-T equipment for any cabling system.

55.7.1 Cabling system characteristics

The cabling system used to support 10GBASE-T requires 4 pairs of ISO/IEC 11801 Class E or Class F balanced cabling with a nominal impedance of 100 Ω . Operation on other classes of cable may be supported if the link segment meets the requirements of 55.7.

Additionally:

a) 10GBASE-T uses a star topology with Class E or Class F balanced cabling used to connect PHY entities.
b) 10GBASE-T is an ISO/IEC 11801 Class E and Class F application with the additional transmission requirements specified in this subclause. The ISO/IEC 11801 cabling limit calculation minimums apply to the link segment specifications.

55.7.2 Link segment transmission parameters

A link segment consisting of up to 100 meters of Class E or up to 100 meters of Class F which meets the transmission parameters of this subclause will provide a reliable medium. The transmission parameters of the link segment include insertion loss, delay parameters, nominal impedance, NEXT loss, ELFEXT, and return loss. In addition, the requirements for the alien crosstalk coupled “between” link segments is specified. Table 55–11 lists the supported cabling types and distances.

Table 55–11— Cabling types and distances

Cabling	Supported link segment distances	Cabling references
Class E / Category 6	55 to 100 m[a]	ISO/IEC TR-24750 / TIA/EIA TSB-155
Class E / Category 6: unscreened	55 m	ISO/IEC TR-24750 / TIA/EIA TSB-155
Class E / Category 6: screened	100 m	ISO/IEC TR-24750 / TIA/EIA TSB-155
Class F	100 m	ISO/IEC TR-24750
new Class E / Augmented Category 6	100 m	ISO/IEC 11801 Ed 2.1 /TIA/EIA-568-B.2-10

[a]Supported link segments up to 100 m shall meet the alien crosstalk to insertion loss requirements specified in 55.7.3.1.2 and 55.7.3.2.2.

The link segment transmission parameters of insertion loss and ELFEXT specified are ISO/IEC 11801 Class E specifications extended by extrapolating the formulas to a frequency up to 500 MHz with appropriate adjustments for length when applicable as specified in ISO/IEC TR-24750 and TIA/EIA TSB-155. The link segment transmission parameters of NEXT loss, MDNEXT loss and Return Loss specified are ISO/IEC

11801 Class E specifications extended beyond 250 MHz by utilizing the equations referenced in TIA/EIA TSB-155.

55.7.2.1 Insertion loss

The insertion loss of each duplex channel shall be less than

$$1.05\left(1.82 \times \sqrt{f} + 0.0169 \times f + \frac{0.25}{\sqrt{f}}\right) + 4 \times 0.02 \times \sqrt{f} \qquad (\text{dB}) \tag{55–11}$$

at all frequencies from 1 MHz to 500 MHz. This includes the attenuation of the balanced cabling pairs, including work area and equipment cables plus connector losses within each duplex channel.

For the purpose of calculating the link segment insertion loss for cabling less than 100 meters the cable insertion loss is assumed to scale linearly with length as defined in (55–26).

55.7.2.2 Differential characteristic impedance

The nominal differential characteristic impedance of each link segment duplex channel, which includes cable cords and connecting hardware, is 100 Ω for all frequencies between 1 MHz and 500 MHz.

55.7.2.3 Return loss

Each link segment duplex channel shall meet or exceed the return loss specified in equation (55–12) at all frequencies from 1 MHz to 500 MHz. The reference impedance for the return loss specification is 100 Ω.

$$\text{Return\_Loss(f)} = \left\{ \begin{array}{ll} 19 & 1 \le f < 10 \\ 24 - 5\log 10(f) & 10 \le f < 40 \\ 32 - 10\log 10(f) & 40 \le f < 400 \\ 6 & 400 \le f \le 500 \end{array} \right\} \qquad (\text{dB}) \tag{55–12}$$

where f is the frequency in MHz.

55.7.2.4 Coupling parameters between duplex channels comprising one link segment

In order to limit the noise coupled into a duplex channel from adjacent duplex channels, Near-End Crosstalk (NEXT) loss and Equal Level Far-End Crosstalk (ELFEXT) are specified for each link segment. In addition, each duplex channel can be disturbed by more than one duplex channel. To ensure the total NEXT loss and FEXT loss coupled into a duplex channel is limited, multiple disturber Near-End Crosstalk (MDNEXT) and multiple disturber ELFEXT (MDELFEXT) is specified.

55.7.2.4.1 Differential Near-End Crosstalk

In order to limit the crosstalk at the near end of a link segment, the differential pair-to-pair Near-End Crosstalk (NEXT) loss between a duplex channel and the other three duplex channels is specified to meet the bit error rate objective specified in 55.1. The NEXT loss between any two duplex channels of a link segment shall be at least

$$\begin{Bmatrix} -20 \times \log 10\left(10^{\frac{74.3 - 15\log 10(f)}{-20}} + 2 \times 10^{\frac{94 - 20\log 10(f)}{-20}}\right) & 1 \le f < 330 \\ 31 - 50 \times \log 10\left(\frac{f}{330}\right) & 330 \le f \le 500 \end{Bmatrix} \quad dB \qquad (55\text{–}13)$$

where f is the frequency in MHz.

Calculations that result in NEXT loss values greater than 65 dB shall revert to a requirement of 65 dB minimum.

55.7.2.4.2 Multiple Disturber Near-End Crosstalk (MDNEXT) loss

Since four duplex channels are used to transfer data between PMDs, the NEXT that is coupled into a data carrying channel will be from the three adjacent disturbing duplex channels.

To ensure the total NEXT coupled into a duplex channel is limited, multiple disturber NEXT loss is specified as the power sum of the individual NEXT losses. The Power Sum loss between a duplex channel and the three adjacent disturbers shall be greater than

$$\begin{Bmatrix} -20 \times \log 10\left(10^{\frac{72.3 - 15\log 10(f)}{-20}} + 2 \times 10^{\frac{90 - 20\log 10(f)}{-20}}\right) & 1 \le f < 330 \\ 28 - 42 \times \log 10\left(\frac{f}{330}\right) & 330 \le f \le 500 \end{Bmatrix} \quad dB \qquad (55\text{–}14)$$

where f is the frequency in MHz.

Calculations that result in PS NEXT loss values greater than 62 dB shall revert to a requirement of 62 dB minimum.

55.7.2.4.3 Multiple-Disturber Power Sum Near-End Crosstalk (PS NEXT) loss

PS NEXT loss is determined by summing the power of the three individual pair-to-pair differential NEXT loss values over the frequency range 1 MHz to 500 MHz. as follows:

$$-10 \times \log 10 \sum_{i=1}^{n} 10^{\frac{-NL(f)i}{10}} \qquad \text{(dB)} \qquad (55\text{–}15)$$

where

NL(f)i is the magnitude in dB of NEXT loss at frequency f of pair combination i

i is the pair-to-pair combination (1 to n)

n is the number of pair-to-pair combinations (n=3)

55.7.2.4.4 Equal Level Far-End Crosstalk (ELFEXT)

Equal Level Far-End Crosstalk (ELFEXT) is specified in order to limit the crosstalk at the far end of each link segment duplex channel and meet the BER objective specified in 55.1.1. Far-End Crosstalk (FEXT) is crosstalk that appears at the far end of a duplex channel (disturbed channel), which is coupled from another duplex channel (disturbing channel) with the noise source (transmitters) at the near end.

FEXT loss is defined as

$$\text{FEXT\_Loss(f)} = 20 \times \log 10\left(\frac{V_{pds(f)}}{V_{pcn(f)}}\right) \qquad \text{(dB)} \tag{55–16}$$

and ELFEXT is defined as

$$\text{ELFEXT(f)} = 20 \times \log 10\left(\frac{V_{pds(f)}}{V_{pcn(f)}}\right) - \text{SLS\_Loss(f)} \qquad (dB) \tag{55–17}$$

where

*V*pds	is the peak voltage of disturbing signal (near-end transmitter)
*V*pcn	is the peak crosstalk noise at far end of disturbed channel
SLS_Loss	is the insertion loss of disturbed channel in dB

The worst pair ELFEXT between any two duplex channels shall be greater than

$$-20 \times \log 10\left(10^{\frac{67.8 - 20\log(10(f))}{-20}} + 4 \times 10^{\frac{83.1 - 20\log 10(f)}{-20}}\right) \qquad \text{(dB)} \tag{55–18}$$

where *f* is the frequency over the range of 1 MHz to 500 MHz.

The numerator of the first term “raised to the power of 10” in equation (55–18) is the cable portion of the duplex channel of 100 meters. The ELFEXT of the cable improves as the cable is reduced in length as defined in equation (55–19). The equation assumes coupling over 100 meters of cable including horizontal cable and cable cords

$$(67.8 - 20\log 10(f)) - 10\left(\log 10(\frac{L}{100})\right) \quad \text{(dB)} \tag{55–19}$$

where L is the length in meters of the link segment.

55.7.2.4.5 Multiple Disturber Equal Level Far-End Crosstalk (MDELFEXT)

Since four duplex channels are used to transfer data between PMDs, the FEXT that is coupled into a data carrying channel will be from the three adjacent disturbing duplex channels. To ensure the total FEXT coupled into a duplex channel is limited, multiple disturber ELFEXT is specified as the power sum of the individual ELFEXT disturbers. The Power Sum loss between a duplex channel and the three adjacent disturbers shall be greater than

$$-20 \times \log 10\left(10^{\frac{64.8 - 20\log 10(f)}{-20}} + 4 \times 10^{\frac{80.1 - 20\log 10(f)}{-20}}\right) \quad (\text{dB}) \tag{55–20}$$

where f is the frequency over the range of 1 MHz to 500 MHz.

55.7.2.4.6 Multiple-Disturber Power Sum Equal Level Far-End Crosstalk (PS ELFEXT)

PS ELFEXT is determined by summing the power of the three individual pair-to-pair differential ELFEXT values over the frequency range 1 MHz to 500 MHz as follows:

$$\text{PSELFEXT(f)} = -10 \times \log_{10} \sum_{i=1}^{i=n} 10^{\frac{-EL(f)i}{10}} \tag{55–21}$$

where

EL(f)i is the magnitude of ELFEXT at frequency f of pair combination i
i is the pair-to-pair combination (1 to n)
n is the number of pair-to-pair combinations (n=3)

55.7.2.5 Maximum link delay

The propagation delay of a link segment shall not exceed 570 ns at all frequencies between 2 MHz and 500 MHz.

55.7.2.6 Link delay skew

The difference in propagation delay, or skew, between all duplex channel pair combinations of a link segment, under all conditions, shall not exceed 50 ns at all frequencies from 2 MHz to 500 MHz. It is a further functional requirement that, once installed, the skew between any two of the four duplex channels due to environmental conditions shall not vary more than 10 ns within the above requirement.

55.7.3 Coupling parameters between link segments

Noise coupled between the disturbed duplex channel in a link segment and the disturbing duplex channels in other link segments is referred to as alien crosstalk noise. To ensure the total Alien NEXT loss and Alien FEXT loss coupled between link segments is limited, multiple disturber Alien Near-End Crosstalk (MD ANEXT) loss and multiple disturber Alien FEXT (MDAFEXT) loss is specified. In addition, to ensure the reliable operation of the link segment, a minimum alien crosstalk to insertion loss ratio are specified.

55.7.3.1 Multiple Disturber Alien Near-End Crosstalk (MDANEXT) loss

In order to limit the alien crosstalk at the near end of a link segment, the differential pair-to-pair Near-End Crosstalk (NEXT) loss between the disturbed duplex channel in a link segment and the disturbing duplex channels in other link segments is specified to meet the bit error rate objective specified in 55.1. To ensure the total Alien NEXT coupled into a duplex channel is limited, multiple disturber Alien NEXT loss is specified as the power sum of the individual Alien NEXT disturbers.

55.7.3.1.1 Multiple-Disturber Power Sum Near-End Crosstalk (PS ANEXT) loss

PS ANEXT loss is determined by summing the power of the individual pair-to-pair differential Alien NEXT loss values over the frequency range 1 MHz to 500 MHz. as follows:

$$-10 \times \log 10 \sum_{i=1}^{n} 10^{\frac{-AN(f)i}{10}} \quad \text{(dB)} \qquad (55\text{–}22)$$

where

AN(f)i is the magnitude in dB of ANEXT loss at frequency f of pair combination i

i is the pair-to-pair combination (1 to n)

n is the number of pair-to-pair combinations between adjacent link segments

Annex 55B provides additional information on identifying the number of adjacent link segments to consider in the PS ANEXT calculation.

The Power Sum ANEXT loss between a disturbed duplex channel in a link segment and the disturbing duplex channels in other link segments shall meet the values determined using equation (55–23) independent of length.

$$PSANEXT \geq \begin{cases} X1 - 10\log 10(\frac{f}{100}) \ (dB) & 1 \leq f \leq 100 \\ X1 - 15\log 10(\frac{f}{100}) \ (dB) & 100 < f \leq 500 \end{cases} \qquad (55\text{–}23)$$

where f is the frequency in MHz and X1 = the value at f=100 MHz. X1 is referred to as the PS ANEXT constant.

The PS ANEXT constant is determined in 55.7.3.1.2 constrained by the ratio of the PS ANEXT to the insertion loss.

The average PS ANEXT loss of the 4-pairs shall meet the values determined using equation (55–24) independent of length

$$PSANEXT\_avg \geq \begin{cases} (X1+1) - 10\log 10(\frac{f}{100}) \ (dB) & 1 \leq f \leq 100 \\ (X1+1) - 15\log 10(\frac{f}{100}) \ (dB) & 100 < f \leq 500 \end{cases} \qquad (55\text{–}24)$$

where f is the frequency in MHz and X1 = the value at f=100 MHz. X1 is referred to as the PS ANEXT constant.

55.7.3.1.2 PS ANEXT loss to insertion loss ratio requirements

To ensure reliable operation, a minimum insertion loss to alien crosstalk ratio shall be maintained. The PS ANEXT loss requirement of 55.7.3.1.1 can be relaxed based on a reduction in the maximum insertion loss specified in 55.7.2.1. The insertion loss reduction can be achieved by utilizing link segments less than 100 meters defined by (55–26) or the insertion loss at 250 MHz of the supported cabling types in Table 55–11.

The adjusted PS ANEXT loss requirement is determined by first calculating the PS ANEXT_constant and utilizing the constant in the PS ANEXT limit line model.

The PS ANEXT_constant is defined by the following equation:

$$\text{PSANEXT\_constant} = 62 - \frac{10GBTIL(250MHz) - (\text{IL}(250MHz)}{1.04} \quad \text{(dB)} \qquad (55\text{–}25)$$

where

10GBTIL(250MHz) is the link segment insertion loss at 250 MHz (equation (55–11))

IL(250MHz) is the insertion loss of a link segment less than 100 meters (equation (55–26)) or the insertion loss at 250 MHz of the supported cabling types in Table 55–11. For the purpose of field testing, IL(250MHz) is the measured insertion loss of the link under test at 250 MHz

The calculated PSANEXT constant values that exceed 33.5 dB shall revert to a value of 33.5 dB.

For the purpose of calculating the link segment insertion loss for cabling less than 100 meters the cable insertion loss is assumed to scale linearly with length.

The scaled link segment is defined by the following equation:

$$\text{Scaled\_10GBT\_IL} = \frac{\text{Length\_m}}{100} \times 1.05\left(1.82 \times \sqrt{f} + 0.0169 \times f + \frac{0.25}{\sqrt{f}}\right) + 4 \times 0.02 \times \sqrt{f} \text{ (dB)} \qquad (55\text{–}26)$$

where Length_m is in meters

.Table 55–12 provides the calculated PS ANEXT_constants for link segments of 100 meters and 55 meters.

Table 55–12— Calculated PS ANEXT Constants

Link Segment Distance	**PS ANEXT_ constant (dB)**	**PS ANEXT_ constant_avg average of the 4-pairs (dB)**	**Insertion Loss at 250 MHz (dB)**
100 meters	62	63	35.9
55 meters	47	48	20.3

Note: For simulating PHY performance to estimate system margin, the PS ANEXT constant average (average of the four pairs) is increased by 2.5 dB to account for an averaging of the PS ANEXT over frequency.

55.7.3.2 Multiple Disturber Alien Far-End Crosstalk (MDAFEXT) loss

In order to limit the alien crosstalk at the far-end of a link segment, the differential pair-to-pair alien far-end crosstalk loss between the disturbed duplex channel in a link segment and the disturbing duplex channels in other link segments is specified to meet the bit error rate objective specified in 55.1. To ensure the total Alien FEXT coupled into a duplex channel is limited, multiple disturber ELFEXT is specified as the power sum of the individual Alien ELFEXT disturbers.

55.7.3.2.1 Multiple-Disturber Power Sum Alien Equal Level Far-End Crosstalk (PS AELFEXT)

Power sum Alien ELFEXT is determined by summing the power of the individual pair-to-pair differential Alien ELFEXT values over the frequency range 1 MHz to 500 MHz as follows:

$$\text{PS AELFEXT(f)} = -10 \times \log_{10} \sum_{i=1}^{i=n} 10^{\frac{-EL(f)i}{10}} \qquad (55–27)$$

where

EL(*f*)i is the magnitude of Alien ELFEXT at frequency *f* of pair combination i
i is the 1, 2, or 3 (pair-to-pair combination)
n is the number of pair-to-pair combinations

The PS AELFEXT between a disturbed duplex channel in a link segment and the disturbing duplex channels in other link segments shall meet the values determined using equation (55–28).

$$PSAELFEXT \geq X2 - 20\log 10\left(\frac{f}{100}\right) \quad (dB) \qquad 1 \leq f \leq 500 \qquad (55–28)$$

where f is the frequency in MHz and X2 = the value at f=100 MHz. X2 is referred to as the PS AELFEXT constant.

The average PS AELFEXT of the 4-pairs shall meet the values determined using equation (55–29).

$$PSAELFEXT\_\text{avg} \geq (X2 + 4) - 20\log 10\left(\frac{f}{100}\right) \quad (dB) \qquad 1 \leq f \leq 500 \qquad (55–29)$$

where f is the frequency in MHz and X2 = the value at f=100 MHz. The value at f=100 MHz is referred to as the PS AELFEXT constant.

The PS AELFEXT constant is determined in 55.7.3.2.2 by the ratio of the PS AELFEXT to the insertion loss and a length correction term. The insertion loss dependent term maintains the required SNR ratio and the IL independent term enables a relaxation of the PS AELFEXT due the reduction in crosstalk coupling for lengths less than 100 meters.

55.7.3.2.2 PS AELFEXT to insertion loss ratio requirements

To ensure reliable operation, a minimum insertion loss to alien crosstalk ratio shall be maintained. The PS AELFEXT requirement of 55.7.3.2.1 can be relaxed based on a reduction in the maximum insertion loss specified in 55.7.2.1 and a reduction in the AELFEXT coupling for cabling lengths less than 100 meters.

The adjusted PS AELFEXT requirement is determined by first calculating the PS AELFEXT constant and utilizing the constant in the PS AELFEXT limit line model of equation (55–30).

The PS AELFEXT constant is defined by the following equation:

$$\text{PS AELFEXT\_constant} = 37.9 - \left(\frac{10GBTIL(250MHz) - IL(250MHz)}{2.29}\right) - 10\left(\log 10\left(\frac{L}{100}\right)\right) \quad \text{(dB)} \qquad (55–30)$$

where

10GBTIL(250MHz) is the link segment insertion loss at 250 MHz (equation (55–11))

IL(250MHz) is the insertion loss of a link segment less than 100 meters (equation (55–26)) or the insertion loss of the supported cabling types in Table 55–11 at 250 MHz. For the purpose of field testing, IL(250MHz) is the measured insertion loss of the link under test at 250 MHz

L is the length in meters of the link segment. The equation assumes coupling over 100 meters of cable including horizontal cable and cable cords

For insertion loss values less than 10 dB at 250 MHz the calculated PSAELFEXT constant values that exceed 32.5 dB shall revert to a value of 32.5 dB.

The field testing of length and insertion loss are addressed in TIA/EIA TSB-155 and ISO/IEC TR-24750.

Table 55–13 provides the calculated PS AELFEXT_constants for link segments of 100 meters and 55 meters.

Table 55–13—Calculated PS AELFEXT Constants

Link Segment Distance	PS AELFEXT_ constant (dB)	PS AELFEXT_ constant_avg average of the 4-pairs (dB)	Insertion loss at 250 MHz (dB)
100 meters	37.9	41.9	35.9
55 meters	33.7	37.7	20.3

55.7.4 Noise environment

The 10GBASE-T noise environment consists of noise from many sources. The primary noise sources that impact the objective BER are the crosstalk and echo interference of a link segment, which are reduced to a small residual noise, and the noise coupled between the link segments referred to as alien crosstalk noise. The remaining noise sources, which are secondary sources, are discussed in the following. The 10GBASE-T noise environment consists of the following:

a) Echo from the local transmitter on the same duplex channel (cable pair). Echo is caused by the hybrid function used to achieve simultaneous bi-directional transmission of data and by impedance mismatches in the link segment. It is impractical to achieve the objective BER without using echo cancellation. Since the symbols transmitted by the local disturbing transmitter are available to the cancellation processor, echo interference can be reduced to a small residual noise using echo cancellation methods.

b) Near-End Crosstalk (NEXT) interference from the local transmitters on the duplex channels (cable pairs) of the link segment. Each receiver will experience NEXT interference from three adjacent transmitters. NEXT cancellers are used to reduce the interference from each of the three disturbing transmitters to a small residual noise. NEXT cancellation is possible since the symbols transmitted by the three disturbing local transmitters are available to the cancellation processor.

c) Far-End Crosstalk (FEXT) noise at a receiver is from three disturbing transmitters at the far end of the duplex channel (cable pairs) of the link segment. FEXT noise can be reduced through cross coupled equalizers although the symbols from the remote transmitters are not immediately available.

d) Inter-Symbol Interference (ISI) noise. ISI is the extraneous energy from one signaling symbol that interferes with the reception of another symbol on the same channel. 10GBASE-T supports the use of Tomlinson Harashima Precoding as a mechanism to reduce the effects of ISI.

e) Noise from non-idealities in the duplex channel, transmitters, and receivers; for example, DAC/ADC non-linearity, electrical noise (shot and thermal), and non-linear channel characteristics. 10GBASE-T limits the effects of some of these non-idealities by a variety of PMA electrical specifications

f) Noise coupled between link segments. Noise coupled between the disturbed duplex channel in a link segment and the disturbing duplex channels in other link segments is referred to as alien crosstalk noise. Since the transmitted symbols from the alien crosstalk noise sources are not available to the cancellation processor (they are in another cable), it is very difficult to cancel the alien crosstalk noise. To ensure robust operation the alien crosstalk is specified in 55.7.3.

g) The background noise for 10GBASE-T is expected not to exceed -150 dBm/Hz. A background noise limit of -150 dBm/Hz was assumed in the 10GBASE-T Matlab simulation models.