

Higher Speed Ethernet – 40 Gb/s and 100 Gb/s copper cable assembly specifications

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Abstract

The IEEE 802.3ba Task Force (the group chartered to develop the 40 Gb/s and 100 Gb/s Ethernet specifications) has identified passive twinaxial copper cable assemblies of lengths up to at least 10 meters as a viable media objective for the interconnection of switch's aggregated in equipment racks, interconnecting high performance computing devices, and for interconnecting network storage devices within the data center, computer room, and central office environments.

The paper will provide a detailed technical overview of the validation of achieving 40 Gb/s and 100 Gb/s Ethernet over 10 meters of passive twinaxial copper cable assemblies. The copper media specifications will be explored in detail including an overview on the specification development analysis methodologies.

1.0 Introduction

Approved in December 2007 the 40 Gb/s and 100 Gb/s Ethernet standards project- designated IEEE 802.3ba-is chartered to extend the Ethernet protocol to operating speeds of 40 Gb/s and 100 Gb/s for both carrier networks (ISP's) and enterprise networks (privately owned) while maintaining maximum compatibility with the installed base of Ethernet interfaces and Ethernet network operation and management.

The 802.3ba project objectives include supporting the media and distances listed in table 1 at a bit error ratio of better than or equal to 10^{-12} . 802.3ba physical layer specifications are for both fiber and copper.

Table 1 IEEE 802.3ba media and distance objectives

Media and distances	40 Gb/s	100 Gb/s
At least 1 m backplane	√	
At least 10 m copper cable assembly	√	√
At least 100 m OM3 multimode fiber	√	√
At least 10 km single mode fiber	√ _a	√
At least 40 km single mode fiber		√

a) under discussion in 802.3ba

The application space for the 40 Gb/s and 100 Gb/s copper cable assembly is within and between racks and cabinets applications and high performance computing. The 10 meter distance provides reasonable coverage given that data center racks and cabinet heights are typically under 2.4 m (8 ft) and multiple racks and

cabinets spans are nominally 1.5 meters; illustrated in figure 1.

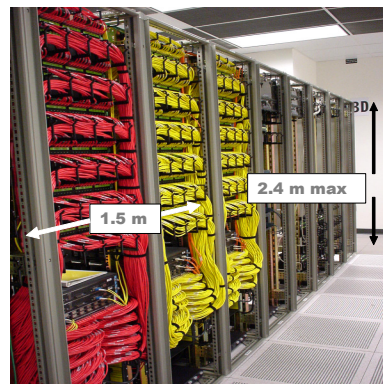


Figure 2 Intra/inter rack applications

2.0 Ethernet physical layer

The 40 Gigabit Ethernet and 100 Gigabit Ethernet physical layer specification, referred to as the "PHY", contains the types of transmitters and receivers and the functions that translate the data into signals (encoding), which are compatible with the cabling type used (e.g., fiber or copper). The encoding function is performed in the physical coding layer (PCS) of the PHY. The 40 Gb/s and 100 Gb/s PHYs use 64B/66B encoded data. The portion of the physical layer responsible for interfacing to the transmission medium is called the physical medium dependent layer (PMD).

The nomenclature used to describe the copper PMD types *40GBASE-CR4* and *100GBASE-CR10* includes the designations indicating speed "40" for 40 Gb/s or "100" for 100 Gb/s, baseband transmission "BASE", the number of 10 Gb/s serial lanes used "4" for 40 Gb/s and "10" for 100

Gb/s, “C” for copper, and the designation “R” referring to the line coding used (e.g., 64B/66B encoded data). 40GBASE-CR4 translates into 40 Gb/s, 64B/66B encoded, baseband transmission, over four copper cable assembly differential pairs.

3.0 Link and channel definitions

For the 40GBASE-CR4 and 100GBASE-CR10 port types the link consists of a copper cable assembly illustrated in figure 2. The Media dependent interfaces (MDIs) refer to the connector interfaces. 40GBASE-CR4 specifies two styles of connectors (MDIs); Style-1 is the quad small form factor pluggable (QSFP) plug and receptacle and Style-2 is the latch-type plug and receptacle with the mechanical mating interface defined by IEC 61076-3-113 and as specified in 10GBASE-CX4. 100GBASE-CR10 specifies only one style of connector; the SFF-8092 plug and receptacle.

The 40GBASE-CR4 and 100GBASE-CR10 channel is defined between the transmitter and receiver blocks to include the transmitter and receiver differential controlled impedance printed circuit board insertion loss and the cable assembly insertion loss.

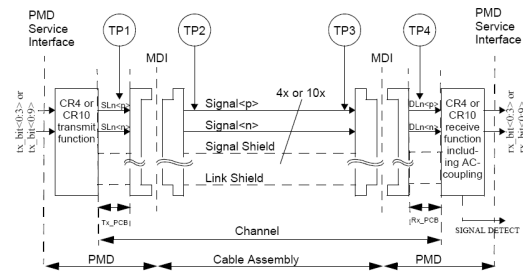


Figure 2 40GBASE-CR4 and 100GBASE-CR10 link diagrams

For conformance testing, four test points are standardized. Cable assembly measurements are to be made between TP1 and TP4. The electrical transmit signal is defined at the output end of the mated connector (TP2) and all receiver measurements and tests are made at the input end of the mated connector (TP3). The transmit function converts four or ten logical bit streams into four or ten separate electrical signal streams.

4.0 Cable assembly characteristics

The 40GBASE-CR4 and 100GBASE-CR10 cable assembly is specified to provide a point-to-point link segment with a minimum reach of 0.5 meters and up to at least 10 meters between the connector receptacles (MDIs) of the network devices.

The twinaxial copper cable assembly consists of shielded signal pairs utilized for differential signaling at 10 Gb/s per differential signal pair. To support 40GBASE-CR4 full-duplex operation, four differential signal pairs or lanes (4-lanes or 4x) in each direction are used for a total of eight differential signal pairs. To support 100GBASE-CR10 full-duplex operation ten differential signal pairs or lanes (10-lanes or 10x) in each direction are used for a total of twenty differential signal pairs. Figure 3 illustrates the twinaxial cables outer diameters for 8 pairs 24 AWG and 20 pairs 24 AWG relative to the outer diameter of a dime and an example of a differential parallel pair with drain wire and aluminum shield.

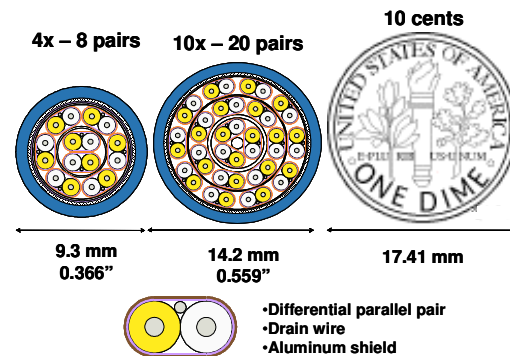


Figure 3 Twinaxial cables

The copper cable assembly specifications are the worst case transmission requirements specified to support 40GBASE-CR4 and 100GBASE-CR10 operation at the 10^{-12} bit error ratio (BER). The differential transmission parameters of the copper cable assembly link segment include insertion loss, return loss, pair-to-pair near-end crosstalk loss (NEXT), multiple disturber NEXT Loss (MDNEXT), pair-to-pair equal level far-end crosstalk (ELFEXT), multiple disturber ELFEXT and delay. Table 2 lists the cable assembly differential parameters and the frequency range specified. Annex A lists a closed form equation for each of the specified parameters.

Table 2 Cable assembly differential parameters

Differential parameter description	f(MHz)	Unit
Maximum Insertion Loss	$100 \leq f \leq 6000$	dB
Minimum Return Loss	$100 \leq f \leq 6000$	dB
Minimum NEXT Loss	$100 \leq f \leq 6000$	dB
Minimum MDNEXT Loss	$100 \leq f \leq 6000$	dB
Minimum ELFEXT	$100 \leq f \leq 6000$	dB
Minimum MDELNEXT	$100 \leq f \leq 6000$	dB

5.0 Validation analysis

The technical feasibility of operating at 10 Gb/s per lane over a 10 meter twinaxial copper cable assembly was established by demonstrating that the 10 meter twinaxial cable assembly transmission characteristics are consistent with the 802.3ap 10GBASE-KR backplane channel characteristics. 802.3ap is the standard for Ethernet operation over electrical backplanes. 802.3ap type 10GBASE-KR specifies 10 Gb/s serial operation over differential, controlled impedance traces on a printed circuit board with 2 connectors and total length up to at least 1 m.

Referring to figure 4, the 802.3ap 10GBASE-KR backplane channel is specified for the following transmission parameters and limits.

- Attenuation and insertion loss: a maximum attenuation is specified due to trace skin effect and dielectric properties as $A_{\max}(f)$ and a fitted attenuation $A(f)$ is defined as the least mean square fit to the measured insertion loss computed. The fitted attenuation of the channel should be less than or equal to $A_{\max}(f)$. A maximum Insertion loss $IL_{\max}(f)$ is defined and the measured insertion loss $IL(f)$ must be less than or equal to $IL_{\max}(f)$.
- Insertion loss deviation (ILD): ILD is defined as the difference between the insertion loss and the fitted insertion loss. ILD is bounded within a region defined by the equations illustrated in figure 7.
- Crosstalk: power sum NEXT (PSNEXT), power sum FEXT (PSFEXT), and power sum differential crosstalk (PSXT); where the power sum differential crosstalk is calculated as the power sum of the individual PSNEXT and PSFEXT disturbers-for 10GBASE-KR a single disturber.
- Return loss
- Insertion loss to crosstalk ratio (ICR): $ICR(f)$ is the ratio of the insertion loss to the total differential crosstalk. It is recommended that the fitted function $ICR_{\text{fit}}(f)$ to $ICR(f)$ be greater than or equal to the specified ICR limit $ICR_{\min}(f)$.

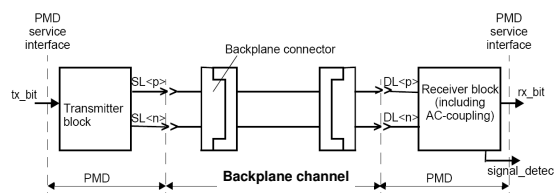


Figure 4 802.3ap backplane channel

Confirmation that the 40GBASE-CR4 and 100GBASE-CR10 channel transmission characteristics defined between the transmitter and receiver blocks illustrated in figure 2 meets

the backplane channel transmission characteristics defined between the transmitter and receiver blocks illustrated in figure 4 was achieved by comparing the 10 meter cable assembly S-parameter measurements to the 802.3ap backplane channel parameter limits.

The transmission of 10 Gb/s on each of the 4-lanes for 40GBASE-CR4 or each of the 10-lanes 100GBASE-CR10 requires additional considerations for multi-disturber noise since each lane can be disturbed by more than one other lane as compared the 10GBASE-KR single backplane channel.

6.0 S-parameter characterization

The s-parameters of a 10 meter cable assembly consisting of a 24 AWG twinaxial cable terminated to QSFP (SFF-8436) plugs were measured with a network analyzer utilizing test adapter fixtures interfacing the network analyzer's SMAs to the QSFP receptacles illustrated in figure 5.

The network analyzer was calibrated at the end of the SMA test cables i.e., the test adapters were included in the measurement results representing an additional loss of 6 inches of FR-4 trace loss to the cable assembly insertion loss.

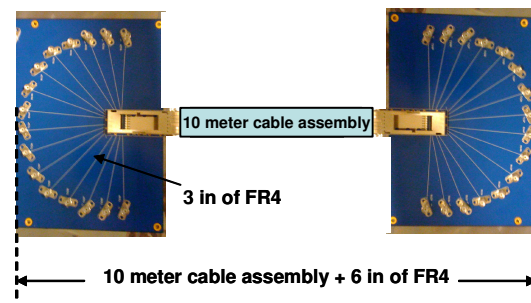


Figure 5 VNA cable assembly test configuration

Figure 6 illustrates comparison of the 10 meter cable assembly measured insertion loss including the test fixture losses to the 10GBASE-KR insertion loss maximum; the insertion loss is less than $IL_{\max}(f)$ for frequencies greater than approximately 3 GHz and exceed $IL_{\max}(f)$ by less than 1 dB for frequencies less than 3 GHz. For 40GBASE-CR4 and 100GBASE-CR10 the maximum cable assembly insertion loss limit will be consistent with twinaxial cable losses rather than losses of the FR-4 printed circuit board.

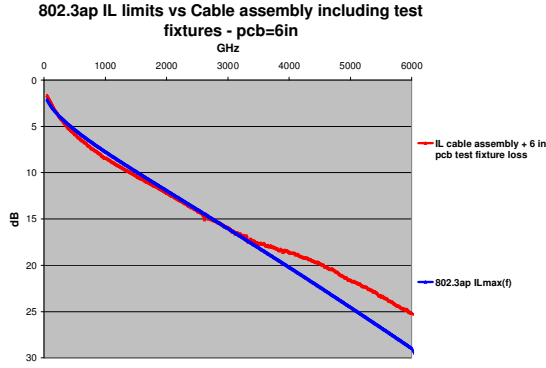


Figure 6 Cable assembly insertion loss

The 10GBASE-KR ILD is bounded within a region defined by the equations illustrated in figure 7. The 10 meter cable assembly measured ILD exhibits a minimum margin of greater than 1 dB over the specified frequency range or 1 GHz to 6 GHz.

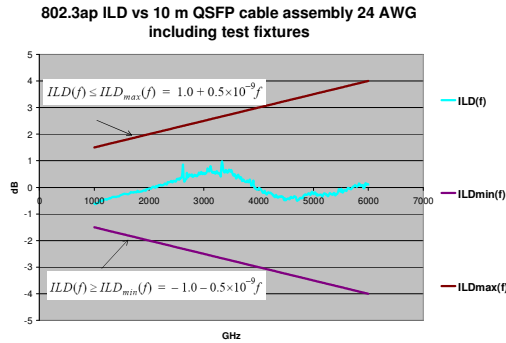


Figure 7 Cable assembly insertion loss deviation

To account for the multi-disturber cable assembly environment, measurements were performed to characterize all of the dominant transmission signal impairments into a single receiver. Figure 8 illustrates the cable assembly measurements of insertion loss and return loss on a single lane as well as the near-end and far-end crosstalk disturbers measured from all the near-end and far-end transmitters in close proximity. The receiver is utilized as a summation reference for the computed insertion loss to crosstalk ratio ICR(f).

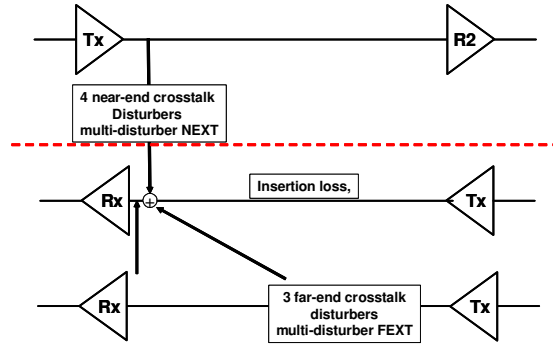


Figure 8 Multi-disturber crosstalk

The differential far-end and near-end crosstalk losses are calculated as the power sum of the individual near-end and far-end crosstalk disturbers. The power sum is determined using equation (1).

$$PS(f) = -10 \times \log \left(\sum_{i=1}^n 10^{-CrosstalkLoss(f)_i / 10} \right) \text{ dB} \quad (1)$$

- where $CrosstalkLoss(f)_i$ is the crosstalk loss, in dB, of disturber i .

The total power sum differential crosstalk (PSXT) is calculated as the power sum of PSNEXT and PSFEXT shown in equation 2.

$$PSXT(f) = -10 \times \log \left(10^{-PSNEXT(f)/10} + 10^{-PSFEXT(f)/10} \right) \text{ dB} \quad (2)$$

- where $PSNEXT(f)$ and $PSFEXT(f)$ are determined using equation (1).

Figure 8 illustrates the measurements of the four near-end crosstalk disturbers and the power sum computation of the four disturbers (PSNEXT) as well as the three far-end crosstalk disturbers and their power sum (PSFEXT). For PSFEXT, the worst case disturber was utilized for all three disturbers yielding a scale factor of 4.77 dB for the worst case disturber.

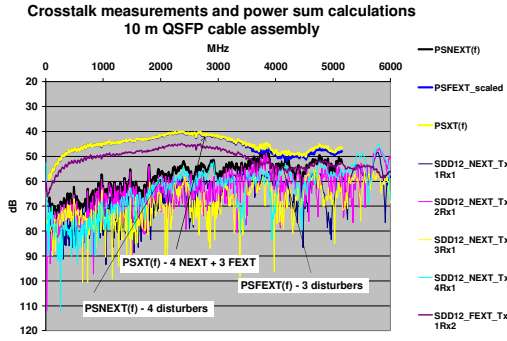


Figure 9 Cable assembly crosstalk

The cable assembly $ICR(f)$ was determined using equation (3). The $ICR_{fit}(f)$ was computed from the equations specified in IEEE 802.3ap subclause 69B.4.6.4 and provided in Annex B. For 10GBASE-KR, it is recommended that $ICR_{fit}(f)$ be greater than or equal to the ICR_{min} determined in equation (4).

$$ICR(f) = -IL(f) + PSXT(f) \text{ dB} \quad (3)$$

$$ICR_{fit}(f) \geq ICR_{min}(f) = 23.2 - 18.7 \log_{10} \left(\frac{f}{5 \times 10^9} \right) \text{ dB} \quad (4)$$

Figure 10 illustrates the cable assembly $ICR(f)$ and the $ICR_{fit}(f)$ compared to the $ICR_{min}(f)$; the plots overlay within tenths of a dB.

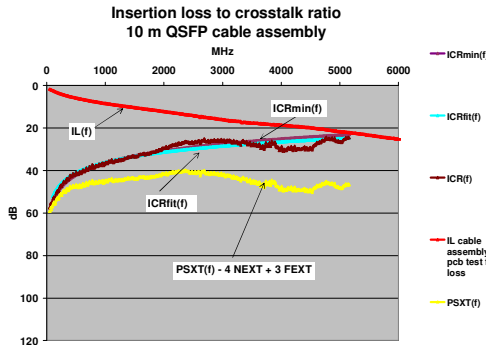


Figure 10 Cable assembly insertion loss to crosstalk ratio

Figure 11 illustrates the cable assembly measured return loss. It is recommended that the measured return loss be greater than or equal to the $RL_{min}(f)$ determined in equations (5-7).

$$RL(f) \geq RL_{min}(f) = 12 \text{ dB} \quad (5)$$

$$\text{for } 50 \text{ MHz} \leq f < 275 \text{ MHz}$$

$$RL(f) \geq RL_{min}(f) = 12 - 6.75 \log_{10} \left(\frac{f}{275 \times 10^6} \right) \text{ dB} \quad (6)$$

$$\text{for } 275 \text{ MHz} \leq f < 3000 \text{ MHz}$$

$$RL(f) \geq RL_{min}(f) = 5 \text{ dB} \quad (7)$$

$$\text{for } 3000 \text{ MHz} \leq f \leq 10321.5 \text{ MHz}$$

Return loss 10 m QSFP cable assembly

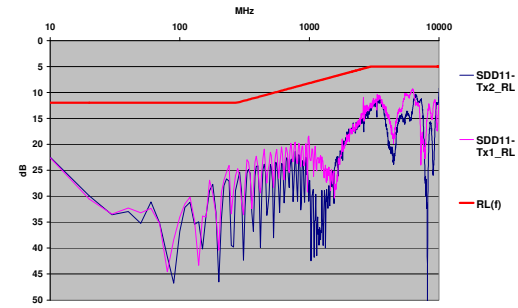


Figure 11 Cable assembly return loss

7.0 Results and Conclusions

The technical feasibility of operating at 10 Gb/s per lane over a 10 meter twinaxial copper cable was proven by demonstrating that the 10 meter twinaxial cable assembly transmission characteristics are consistent with the 802.3ap 10GBASE-KR backplane channel characteristics. 802.3ap is the standard for Ethernet operation over electrical backplanes. 802.3ap type 10GBASE-KR specifies 10 Gb/s serial operation over differential, controlled impedance traces on a printed circuit board with 2 connectors and total length up to at least 1 m.

8.0 Acknowledgements

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Annex A Cable assembly specifications

Table 3 lists the IEEE 802.3ba 40GBASE-CR4 and 100GBASE-CR10 cable assembly differential parameters and closed form equations for the limit specified for each parameter. The “to be determined” (TBD) placeholders will be determined from regressions to the cable assembly measurements used in the analysis validation.

Table 3 Cable assembly differential parameters

Description	Value	Unit
$Insertion\ Loss(f) \leq TBD \sqrt{f} + TBD \times f + \frac{TBD}{\sqrt{f}}$	TBD	dB
$NextLoss(f) \geq TBD - TBD \times \log\left(\frac{f}{TBD}\right)$	TBD	dB
$ReturnLoss(f) \geq TBD$	TBD	dB
$MDNextLoss(f) \geq TBD - TBD \times \log\left(\frac{f}{TBD}\right)$	TBD	dB
$ELFEXT(f) \geq TBD - TBD \times \log\left(\frac{f}{TBD}\right)$	TBD	dB
$MDELFT(f) \geq TBD - TBD \times \log\left(\frac{f}{TBD}\right)$	TBD	dB

Annex B 10GBASE-KR ICR_{fit} computation

Assuming ICR is computed at N uniformly-spaced frequencies f_n spanning the frequency range f_a to f_b , ICR_{fit} may be computed using equations (B1) through (B5). The values of f_a and f_b for 10GBASE-KR are $f_a=0.100$ GHz and $f_b= 5.15625$ GHz.

$$x_{avg} = \frac{1}{N} \sum_n \log(f_n) \quad (B1)$$

$$ICR_{avg} = \frac{1}{N} \sum_n ICR(f_n) \quad (B2)$$

$$m_{ICR} = \frac{\sum_n (\log(f_n) - x_{avg})(ICR(f_n) - ICR_{avg})}{\sum_n (\log(f_n) - x_{avg})^2} \quad (B3)$$

$$b_{ICR} = ICR_{avg} - m_{ICR} x_{avg} \quad (B4)$$

$$ICR_{fit}(f) = m_{ICR} \log(f) + b_{ICR} \quad (B5)$$