

Beyond 100G Client Optics

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ABSTRACT

Major client optics applications are the high-density data center, structured data center, carrier central office, general data center, and metro inter data center, corresponding to link reaches from 100 m to 40 km. First-generation 100G multimode fiber and single-mode fiber client optics are based on $10 \times 10\text{G}$ electrical lane and $10 \times 10\text{G}$ or $4 \times 25\text{G}$ optical lane architectures. Next-generation 100G MMF and SMF client optics will be based on $4 \times 25\text{G}$ electrical lane and $4 \times 25\text{G}$ optical lane architecture. Beyond 100G, it is likely the next standard will be 400G based on extensions of 100G technologies. Beyond 400G, 1.6T is a possible standard, requiring highly novel technologies.

INTRODUCTION

First-generation 100G optics are deployed into high-performance computing (HPC), Internet data center (IDC), and carrier central office (CCO) high-end applications. Next-generation 100G optics are now being defined and standardized to enable continued network bandwidth growth and extension into high-volume applications. To support further bandwidth growth, the communications industry is investigating technologies beyond 100G. This article contributes client optics considerations.

First is a description of major client optics applications. Second is the establishment of a technology baseline by describing first-generation and next-generation 100G client optics. Third, on the basis of historical, economic, technology, and bandwidth growth considerations, 400G is identified as the likely next standard, and 400G client optics based on 100G technologies are described. Finally, considerations beyond 400G are introduced.

CLIENT OPTICS APPLICATIONS

Major 10G, 40G, and 100G client optics applications are listed in Table 1. Their reach is from less than 100 m to 40 km, and their loss budget is from 2 dB to 21 dB. They will continue as major applications beyond 100G. Multi-gigabit Ethernet optics standards are specified by the IEEE 802.3 Working Group (WG), simply referred to as IEEE in this article, are preceded by 802.3 and contain GE abbreviation in their name. For example, 10GE designates 10-Gb/s data rate specifications. Multi-gigabit Transport optics standards are specified by the Interna-

tional Telecommunication Union — Telecommunication Sector (ITU-T) Study Group 15 (SG15), simply referred to as ITU-T in this article, and start with the letter G referring to their Recommendation. The optical Transport unit (OTU) abbreviation designates Transport rate specifications in the G.709 Recommendation. For example, OTU-2, OTU-3, and OTU-4 designate 10G, 40G, and 100G Transport rate specifications, respectively. The IEEE and ITU-T coordinate their standards development activities through formal liaison letters and informal discussions.

HIGH-DENSITY DATA CENTER MMF OPTICS

The majority of data center optics use multimode fiber (MMF) technology because of low cost. Specific applications are intra-rack single span links and structured links as described in [1]. Structured links have only two or four patch panel fiber connections, limiting their loss budget, therefore resulting in reduced transmitter and receiver requirements.

The 10GE-SR duplex MMF optics specifications are defined in the 802.3ae-2002 standard. The maximum specified reach is 300 m, although most deployed links are below 100 m. The 10GE-SR optics use a single vertical cavity surface emitting laser (VCSEL) transmitter and are packaged in the small form-factor pluggable (SFP+) module, establishing the baseline bit-per-second cost vs. volume reference curve for higher-data-rate structured MMF and single-mode fiber (SMF) optics.

STRUCTURED DATA CENTER SMF OPTICS

During the development of the 802.3ae-2002 standard, the IEEE studied the feasibility of 10G duplex SMF optics, optimized for data center links shorter than 1 or 2 km. The lower-cost Fabry-Perot (FP) laser transmitter was considered instead of the distributed feedback (DFB) laser transmitter used in 10 km general data center optics. Ultimately, a separate duplex SMF standard was not adopted because at the time 99 percent of data center links were shorter than 300 m, which is supported by the low-cost duplex MMF 10GE-SR optics. Since then, the emergence of large IDCs created more links longer than 300 m. This was recognized during the development of the 802.3ba-2010 standard, and a separate requirement for 400–1000 m duplex SMF structured data center optics was identified

Client optics application and media type	High-density data center parallel MMF	Structured data center duplex SMF	Carrier central office duplex SMF	General data center duplex SMF	Metro inter data center duplex SMF
Max. reach	100 m	1000 m	2 km	10 km	20, 30, 40 km
Min. loss budget	2 dB	2 dB	4 dB	6 dB	11 to 21 dB
Bit-per-second cost vs. volume reference curve	10G VCSEL	10G VCSEL	10G DFB laser	10G DFB laser	10G EML
10G standard	Duplex MMF 10GE-SR	None	OC-192 SR-1 G.693 10G	10GE-LR	10GE-ER G.959.1 10G
40G standard	40GE-SR4	None	40GE-FR G.693 40G	40GE-LR4 G.695 10G	Proposed 40GE-ER4
100G standard	100GE-SR10	None	None	100GE-LR4 G.959.1 25G	100GE-ER4 G.959.1 25G

Table 1. Major client optics applications.

[2]. This requirement extended below 400 m when 100 m was the maximum reach supported by 40G and 100G high-density data center parallel MMF optics. However, since this was just one of several identified duplex SMF reach requirements, the IEEE adopted a single 10 km reach objective to support all 40G and 100G data center duplex SMF applications. As a result, there is no duplex SMF optics standard specifically for the structured data center application.

Block diagrams of structured data center links are shown in Fig. 1 and described in [1]. The defining characteristics of structured data center duplex SMF optics is a minimum loss budget of 2 dB, link budget penalties supporting up to 1000 m SMF reach, and bit-per-second cost comparable to VCSEL transmitter optics. Significantly lower cost than that of general data center duplex SMF optics is potentially enabled by ~6 dB lower link budget, which creates opportunities for new technologies.

CARRIER CENTRAL OFFICE SMF OPTICS

The defining characteristics of CCO duplex SMF optics are a minimum loss budget of 4 dB, and link budget penalties supporting up to 2 km duplex SMF reach. All IEEE and ITU-T specified 10G and 40G CCO optics deployed during the past decade have at least this level of performance. The 10G CCO optics are tri-rate, meeting G.693 10G, 10GE-LR, and OTU-2 specifications. Even though the loss and reach requirements in a CCO are lower than for general data center links, there is no cost advantage for development of dedicated CCO 10G optics. The 40G CCO optics are now also tri-rate, meeting G.693 40G, 40GE-FR, and OTU-3 specifications. The CCO 100G optics are dual-rate, meeting 100GE-LR4 and G.959.1 25G specifications.

GENERAL DATA CENTER SMF OPTICS

The defining characteristics of general data center optics are a minimum loss budget of 6 dB, and link budget penalties supporting up to 10

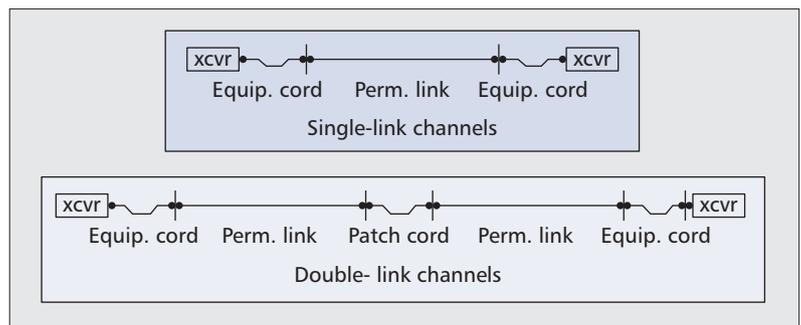


Figure 1. Structured data center links [1].

km duplex SMF reach. All 10G, 40G, and 100G general data center optics specified by the IEEE and ITU-T deployed during the past decade have at least this level of performance. The 10GE-LR duplex SMF optics specifications are defined in the 802.3ae-2002 standard, use a single DFB laser transmitter, and are packaged in the 10G form-factor pluggable (XFP) or SFP+ module. The SFP+ implementation establishes the baseline bit-per-second cost vs. volume reference curve for higher-data-rate general data center SMF optics.

METRO INTER-DATA CENTER SMF OPTICS

Metro inter-data center 10G optics defined by the ITU-T have a minimum loss budget of 11 dB and link budget penalties supporting up to 20 km SMF reach, while those defined by the IEEE have a minimum loss budget of 15 dB and link budget penalties supporting up to 40 km SMF reach. Metro inter-data center 100G optics are similarly defined by the IEEE and ITU-T with a minimum loss budget of 21 dB, and link budget penalties supporting up to 40 km SMF reach. The baseline bit-per-second cost vs. volume reference curve is established by the 10GE-ER electro-absorption modulated laser (EML) transmitter optics defined in the 802.3ae-2002 standard.

Baseline application	High density data center parallel MMF	Structured data center duplex SMF	General data center duplex SMF	Metro inter data center duplex SMF
Max. reach	70 m	1000 m	10 km	40 km
Min. loss budget	2 dB	2 dB	6 dB	21 dB
100G standard	Proposed 100GE-SR4	Proposed 100GE-nR4	100GE-LR4	100GE-ER4

Table 2. Baseline 100G client optics specified in IEEE 802.3ba-2010, or proposed for study in IEEE 802.3 Next Generation 100-Gb/s Optical Ethernet Study Group [7].

FIRST-GENERATION 100G OPTICS

MMF OPTICS

The 100GE-SR10 parallel MMF optics specifications are defined in the 802.3ba-2010 standard, use a VCSEL photonic integrated circuit (PIC) or array transmitter, and are described in detail in [3]. The highest front panel port density is achieved by packaging the 100GE-SR10 optics in the CXP (100G extended-capability pluggable) module, which supports MMF but not SMF optics. The 100GE-SR10 optics are also packaged in the larger CFP (100G form-factor pluggable) module, which is specified by the CFP multi-source agreement (MSA) [4], and supports both MMF and SMF optics.

SMF OPTICS

The 100GE-LR4 and 100GE-ER4 duplex SMF optics specifications are defined in the 802.3ba-2010 standard. The OTU-4 equivalent optics specifications are in the G.959.1 25G standard. The CCO 100G applications are supported by dual rate interfaces, similar to support at 10G. Initial implementations use discrete 25G EML transmitters, are in the CFP module [4], and are now transitioning to lower cost DFB laser PIC transmitters [5].

NEXT GENERATION BASELINE 100G OPTICS

Next-generation 100G client optics are under discussion in the IEEE 802.3 Next Generation 100-Gb/s Ethernet Optics Study Group (NG 100G SG) [6]. Baseline 100G optics operating at the 25.75-Gb/s standard Ethernet line rate, proposed for study in NG 100G SG [7] are listed in Table 2. Since the existing 100GE-LR4 optics standard continues as the optimum specification for general data center applications, no replacement standard has been proposed. The existing 100GE-ER4 optics standard also continues to support the 40 km metro application.

HIGH DENSITY DATA CENTER MMF OPTICS

A block diagram of the proposed 100GE-SR4 optics is shown in Fig. 2. Electrical and optical lane width reduction from $10 \times 10G$ to $4 \times 25G$

allows a 2.5 times increase in front panel density and 2 times increase in cabling density. Maximum reach on parallel MMF is under investigation by NG 100G SG, and will in part depend on the type of electrical interface selected. The retimed proposed CAUI-4 input/output (I/O) will support longer reach than the unretimed proposed CPPI-4 I/O. The proposed 100GE-SR4 optics can be packaged in the new CFP2 (2 times CFP density) and CFP4 (4 times CFP density) modules [4], and possibly in the 25G quad small form-factor pluggable (QSFP+) module.

STRUCTURED DATA CENTER SMF OPTICS

The driving requirement of structured data center duplex SMF optics is bit-per-second cost comparable to 10G VCSEL transmitter optics. This may be enabled by a ~ 6 dB lower link budget than specified for the 100GE-LR4 general data center optics. The NG 100G SG is investigating the technical feasibility and broad market potential of such a standard. Since it has not been adopted, it is generically referred to as 100GE-nR4. It may turn out that the technical feasibility or market potential is insufficient to justify adopting this standard in the IEEE.

The proposed 100GE-nR4 optics, based on the lower-cost DFB laser and PIC transmitter, have the same block diagram as the 100GE-LR4 optics shown in Fig. 3. Their specifications can be derived from the 100GE-LR4 specifications, for example, by reducing the transmitter output optical power by ~ 6 dB and keeping similar receiver specifications. Alternately, transmitter power reduction can be traded off for receiver sensitivity decrease. Reusing the 100GE-LR4 wavelength-division multiplexing (WDM) grid enables full interoperability over reaches up to 1000 m.

Alternate $4 \times 25G$ PIC transmitter technologies are possible:

- Uncooled DFB laser
- Silicon modulator
- Indium Phosphide modulator
- Long-wave VCSEL
- Parallel SMF

A coarse WDM (CWDM) grid enables uncooled optics operation, which can also reduce power consumption. Architectures using fewer than $4 \times 25G$ optical lanes can also be considered, using higher order modulation.

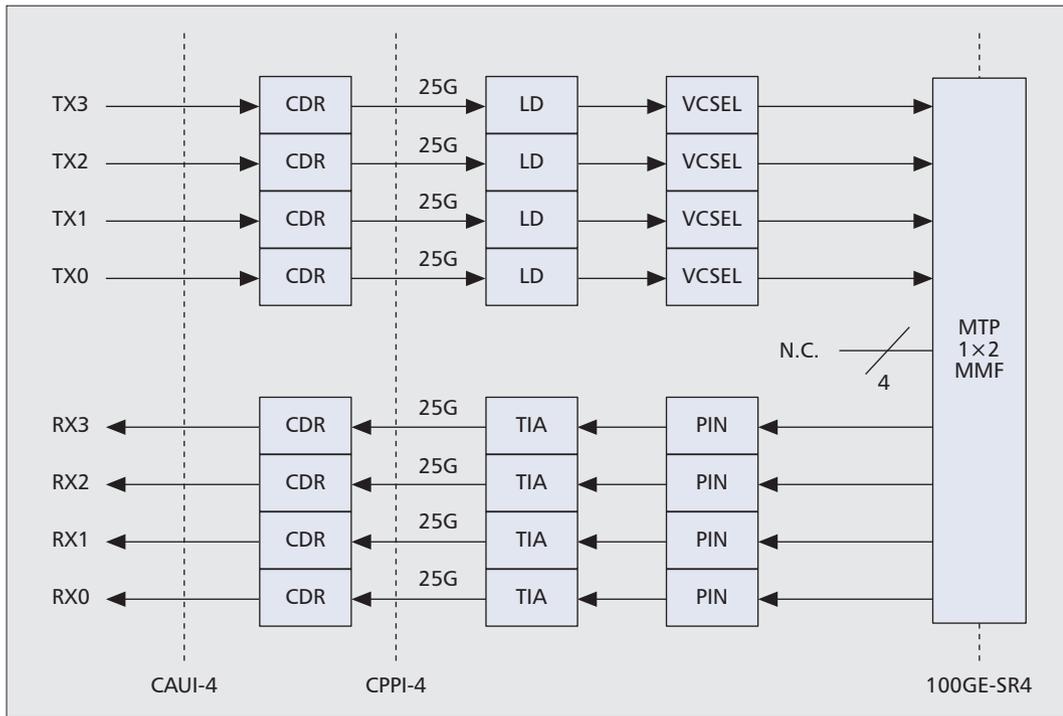


Figure 2. Proposed Next Generation 100G high-density data center parallel MMF optics.

The CCO 100G applications are supported by dual rate interfaces, similar to support at 10G. Initial implementations use discrete 25G EML transmitters, are in the CFP module, and are now transitioning to lower cost DFB laser PIC transmitters.

GENERAL DATA CENTER SMF OPTICS

A block diagram of the 100GE-LR4 optics is shown in Fig. 3, and implementation details are discussed in [8]. Electrical lane width reduction from $10 \times 10G$ (CAUI) to $4 \times 25G$ (proposed CAUI-4) allows a $2.5 \times$ increase in front panel density. The next-generation 100GE-LR4 optics can be packaged in the new CFP2 and CFP4 modules [4].

METRO INTER-DATA CENTER SMF OPTICS

A block diagram of the 100GE-ER4 optics is similar to the 100GE-LR4 optics shown in Fig. 3. Instead of the DFB laser PIC transmitter, an EML PIC or equivalent high extinction ratio (ER) transmitter is required. A semiconductor optical amplifier (SOA) is added before the optical demultiplexer to increase receiver sensitivity and support the higher loss budget [8]. Electrical lane width reduction from $10 \times 10G$ to $4 \times 25G$ allows a 2.5 times increase in front panel density.

NEXT-GENERATION FEC 100G OPTICS

Forward error correction (FEC) 100G client optics operating from 25.75 Gb/s (0 percent overhead) to 27.95 Gb/s (8 percent overhead) line rate are under consideration in NG 100G SG. Examples illustrating various ways that FEC coding gain can be used [7] are listed in Table 3. Traditionally, a major limitation of using FEC for Ethernet applications is increased link latency. Proper FEC code design has been shown [9] to reduce the latency below 100 ns, making it negligible. The IEEE may decide to develop several, one, or no FEC optics standards, but is unlikely to adopt all Table 3 examples.

Since 28G VCSELs are under development for 32x fiber channel applications, and 28G DFB laser PICs are under development for OTU-4 applications, 28G FEC rate fully exploits the capability of mainstream laser technology. Use of exactly the OTU-4 27.95 Gb/s rate results in common Ethernet and Transport modules and test equipment. The 28G FEC rate has ~ 3 dB optical coding gain with ~ 2 dB available to increase the loss budget. The remaining ~ 1 dB can be allocated to compensate for reduced receiver sensitivity due to higher line rate and additional penalties. Lower FEC rates under study, including 0 percent overhead gain, result in higher latency or lower coding gain.

HIGH DENSITY DATA CENTER MMF OPTICS

The proposed 100GE-SR4f optics block diagram is the same as shown in Fig. 2. The ~ 2 dB loss budget increase leads to ~ 40 percent reach increase.

CARRIER CENTRAL OFFICE SMF OPTICS

The proposed 100GE-nR4f duplex SMF optics block diagram is the same as the 100GE-LR4 diagram shown in Fig. 3. The ~ 2 dB loss budget increase leads to a minimum 4 dB loss budget enabling support of the CCO application. Alternately, the 1000 m duplex SMF loss budget can be decreased by ~ 2 dB, lowering the cost of the proposed 100GE-nR4f structured data center optics.

METRO INTER DATA CENTER SMF OPTICS

The proposed 100GE-LR4f optics block diagram is the same as shown in Fig. 3. The ~ 2 dB loss budget increase can go up an additional 3 dB by operating the DFB laser transmitter at a higher optical output power, taking advantage of recent higher eye safety measurement limits, resulting

IEEE and ITU-T are strongly committed to full Ethernet and Transport compatibility in future standards. Efficient and transparent Ethernet support over Transport will be an important consideration in the selection of data rates beyond 100G.

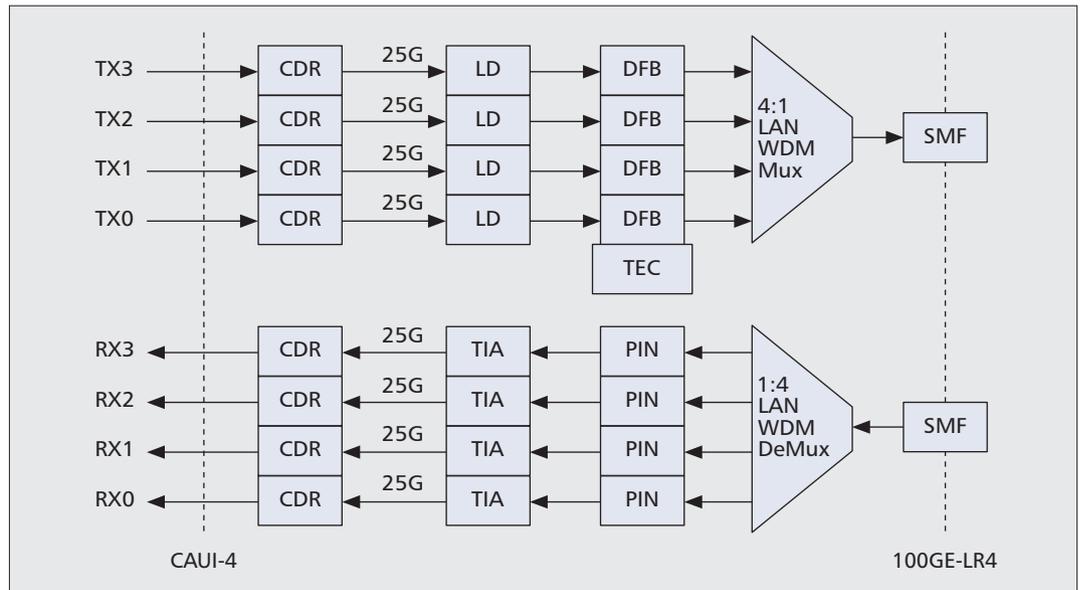


Figure 3. Proposed next-generation 100G general data center duplex SMF optics.

in 11 dB loss budget supporting 20 km applications. High-loss data center applications are also enabled, for example, those requiring multiple in-line passive loss elements. This example is compelling because a 20 km metro application would be supported with lower-cost DFB laser transmitter optics instead of EML transmitter optics.

The proposed 100GE-ER4f optics are another example of using FEC coding gain to reduce the minimum receiver sensitivity by ~2 dB, which improves yield and reduces cost. The 40 km reach remains unchanged.

MULTILINK GEARBOX 100G OPTICS

A block diagram of the proposed multilink gearbox (MLG) 100G optics is shown in Fig. 4. The MLG standard is under development in the Optical Internetworking Forum (OIF) [10], and the approved MLG OIF project proposal is available in [4]. As shown in Fig. 4, MLG expands $4 \times 25\text{G}$ I/O into 10 independent 10G Ethernet links for a total bandwidth of 100G. This enables very high 10G switch port density, determined by the width of four electrical I/O lanes instead of 10 electrical I/O lanes.

If used in a CFP4 module [4], a standard host card can support $16 \times 100\text{G}$ ports in a single row configuration, or $32 \times 100\text{G}$ ports in a belly to belly configuration, which gives $160 \times 10\text{G}$ ports or $320 \times 10\text{G}$ ports, respectively. Such dense configurations will require advanced thermal management techniques.

NEXT DATA RATE BEYOND 100G

HISTORICAL STANDARD DATA RATE STEPS

Historically, Ethernet data rates have lagged behind transport data rates, enabling Ethernet to leverage technology developed for transport. This was one factor enabling $10 \times$ Ethernet standard rate steps compared to $4 \times$ transport stan-

dard rate steps. An alignment of rates occurred at 100G, which means that going forward, technology challenges will be equally faced. A likely common $4 \times$ next rate step will result in 400G Ethernet and Transport standards.

ETHERNET AND TRANSPORT ALIGNMENT CONSIDERATIONS

At 10G, ITU-T defined the OTU-2 rate to be ~10.7 Gb/s to efficiently transport ~10 Gb/s rate data. IEEE 802.3ae-2002 subsequently defined two 10G Ethernet rates; ~10.3 Gb/s LAN rate for data center applications, and ~10-Gb/s wide area network (WAN) rate for Transport.

For cost reasons, LAN rate became dominant, requiring direct transport without conversion to WAN rate as intended. This created a problem because the LAN rate is greater than the OTU-2 payload rate. One solution removes the LAN preamble and interpacket gap (IPG), resulting in possible loss of proprietary control words, which is not transparent. Alternatively, the OTU-2 rate can be increased (overclocked) to a higher OTU-2e rate. This does not aggregate in the Transport hierarchy. The same problems exist when transporting $4 \times 10\text{G}$ LAN rate data over OTU-3.

To avoid similar problems, IEEE 802.3ba-2010 defined 40G Ethernet to have a small control word set to enable fixed transcoding to OTU-3, resulting in transparent support for 40G Ethernet over 40G Transport. Similarly, ITU-T specified ~112-Gb/s as the OTU-4 rate to efficiently carry ~103 Gb/s Ethernet data, resulting in transparent support for 100G Ethernet over 100G Transport.

IEEE and ITU-T are strongly committed to full Ethernet and Transport compatibility in future standards. Efficient and transparent Ethernet support over Transport will be an important consideration in the selection of data rates beyond 100G. Joint technical and economic feasibility considerations of client and line side

FEC extended application	High-density data center parallel MMF	Carrier central office duplex SMF	Metro inter data center duplex SMF	Metro inter data center duplex SMF
Max. reach	100 m	2 km	20 km	40 km
Min. loss budget	4 dB	4 dB	11 dB	21 dB
100G standard	Proposed 100GE-SR4f	Proposed 100GE-nR4f	Proposed 100GE-LR4f	Proposed 100GE-ER4f

Table 3. Example FEC 100G client optics proposed for study in IEEE 802.3 Next Generation 100-Gb/s Optical Ethernet Study Group [7].

optics will likely lead to 400G as the next Ethernet and Transport standards.

ETHERNET TECHNOLOGY AND INVESTMENT CONSIDERATIONS

End users require that the next Ethernet data rate beyond 100G provide a meaningful increase in bandwidth while staying on the 100G technology bit-per-second cost vs. volume curve. Suppliers need to leverage the large 100G R&D investment and ramping 100G product volumes. This drives the next data rate to be based on extending 100G technology, which is feasible for rates up to 400 Gb/s. Higher Ethernet rates (e.g., 1 Tb/s) will require highly novel technologies, a huge R&D investment, and a lengthy R&D period, significantly postponing availability of the next rate standard.

TRANSPORT TECHNOLOGY AND INVESTMENT CONSIDERATIONS

A key requirement in the selection of the future OTU-5 rate, the Transport rate after OTU-4, is increase in spectral efficiency to decrease bit-per-second cost. The practical limit of spectral efficiency of existing SMF fiber for Transport reaches longer than 1000 km was shown to be ~4 b/s/Hz [11]. Spectral efficiency of 100 Gb/s in a 50 GHz channel is ~2 b/s/Hz. Doubling of

spectral efficiency can be achieved by going to 400 Gb/s in a 100 GHz channel. However, higher rates above 400 Gb/s do not increase spectral efficiency, but require more bandwidth. 400G implementations are also the practical limit of extension of 100G Transport technology. A more spectrally efficient higher Transport rate will require highly novel technologies and a huge R&D investment.

400G OPTICS

FIRST GENERATION MMF OPTICS

The block diagram of the proposed 400GE-SR16 parallel MMF optics for high-density data center applications is shown in Fig. 5. A critical technology, currently in development, is a 2 × 16 multifiber termination push-on (MTP) connector shown in Fig. 6. It uses the same core technology originally developed by NTT researchers [12], and used in existing 1 × 12 and 2 × 12 MTP connectors. The vertical row separation is maintained at 0.5 mm, and the horizontal element pitch is maintained at 0.25 mm. By preserving all the MTP critical dimensions and only increasing the connector width by 1 mm, the development risk is minimized.

The required 16 × 25G VCSEL PIC transmitter technology is an extension of 12 × 10G arrays used in the 100GE-SR10 optics and 4 × 25G arrays in development for the proposed 100GE-

400G implementations are also the practical limit of extension of 100G Transport technology. A more spectrally efficient higher Transport rate will require highly novel technologies and a huge R&D investment.

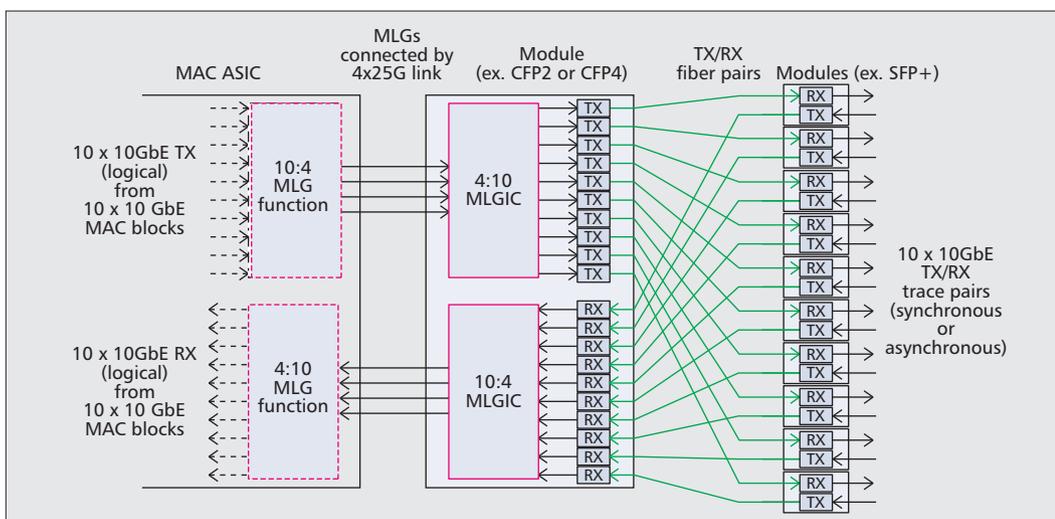


Figure 4. Proposed multilink gearbox (MLG) 100G optical port expander module connected to 10 SFP+ modules.

If 400G becomes the next Ethernet standard after 100G, then 1T is unlikely as a follow-on standard because it is only a 2.5x rate increase. This is not a significant bandwidth increase and is unlikely to justify the huge R&D investment required.

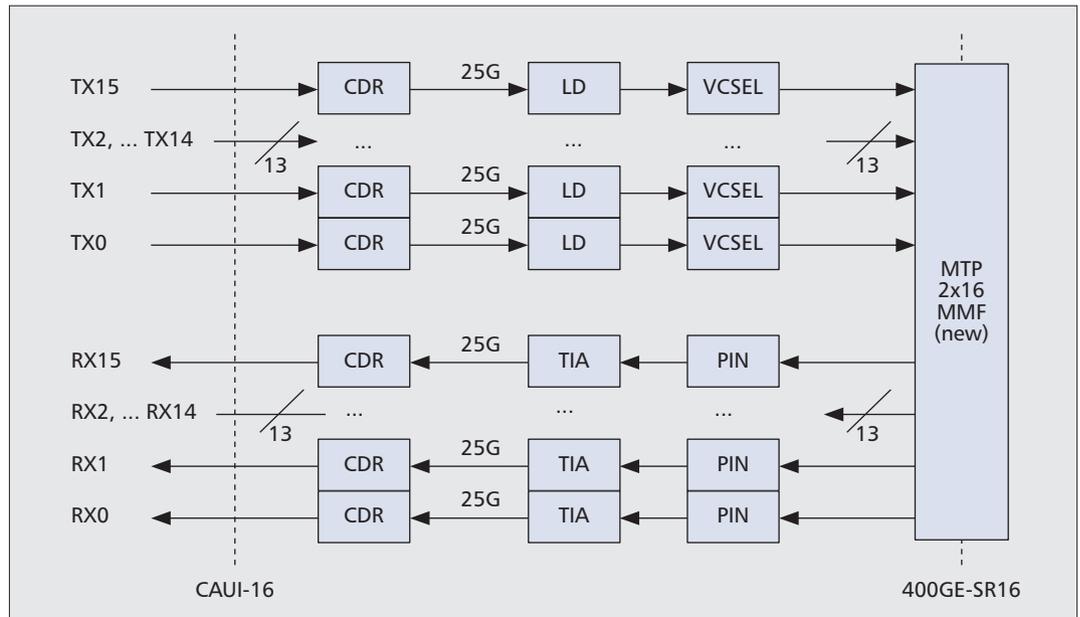


Figure 5. Proposed First Generation 400G high-density data center parallel MMF optics.

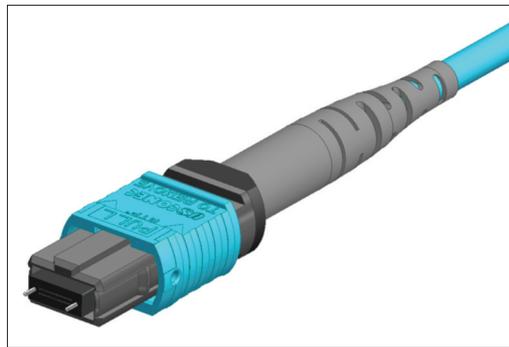


Figure 6. 2 × 16 parallel MMF MTP connector and cable assembly, courtesy US Conec.

SR4 optics. FEC optical coding gain can increase loss budget and reach. The 16-lane architecture is also a candidate for high-volume computer bus applications.

FIRST GENERATION SMF OPTICS

A block diagram of the proposed 400GE-nR16 duplex SMF optics for structured data center applications is shown in Fig. 7. An extension of four 100GE-LR4 center wavelengths to 16 proposed 400GE-nR16 center wavelengths is listed in Table 4. The third column in the table (1310 nm band) lists the four existing 100GE-LR4 center wavelengths. The low loss budget of the structured data center application combined with the high optical output power of DFB laser PIC transmitters compensates for the high loss of the optical 16:1 multiplexer and 1:16 demultiplexer. FEC optical coding gain can provide additional loss compensation.

The block diagram of the proposed 400GE-LR16 duplex SMF optics for general data center applications is similar to the one shown in Fig. 7. Higher receiver sensitivity than for the proposed 400GE-nR16 optics is required to support the

minimum 6 dB loss budget and link budget penalties supporting up to 10 km SMF reach. One alternative is an SOA, which can be placed before the WDM demultiplexer. Since an SOA has extinction ratio and power variation limitations, another alternative is to replace the 25G PIN photodiodes (PDs) with 25G avalanche PDs (APDs). The proposed 400GE-LR16 optics can use the center wavelengths listed in Table 4.

NEXT-GENERATION 400G OPTICS

Increasing the number of parallel fibers and wavelengths increases optics density. However, 400G 16 × 25G electrical lanes have the same switch application-specific integrated circuit (ASIC) and electrical connector I/O bandwidth density as 100G 4 × 25G electrical lanes.

I/O bandwidth is increased by reducing the number of electrical lanes. Electrical line rate increase from 25G to 50G may be possible, but will face severe signal integrity challenges. An alternative is multilevel modulation, such as 4-level pulse amplitude modulation (PAM-4), which reduces the number of electrical lanes to eight. Higher order modulation is required to further reduce the number of electrical lanes. Another alternative is to change the front panel paradigm and place the optics on the host card, physically close to or inside the switch ASICs. Higher order modulation can also be considered for reducing the number of optical lanes.

BEYOND THE NEXT DATA RATE

BANDWIDTH INCREASE AND INVESTMENT CONSIDERATIONS

If 400G becomes the next Ethernet standard after 100G, 1T is unlikely as a follow-on standard because it is only a 2.5x rate increase. This is not a significant bandwidth increase and is unlikely to justify the huge R&D investment required. Similarly, 1.2T is only a 3x rate

Center wavelength designations	1330 nm band center wavelengths (nm)	1310 nm band center wavelengths (nm)	1290 nm band center wavelengths (nm)	1270 nm band center wavelengths (nm)
L3	1327.69	1309.14	1291.10	1273.55
L2	1323.00	1304.58	1286.66	1269.23
L1	1318.35	1300.05	1282.26	1264.95
L0	1313.73	1295.56	1277.89	1260.69

Table 4. Proposed 400GE-nR16 center wavelengths.

A direct extension of 100G technology to 1.6T requires $64 \times 25\text{G}$ direct modulation lasers or 25G modulator-lasers. This is not practical because of connector complexity, PCB routing, switch ASIC I/O, and cost limitations.

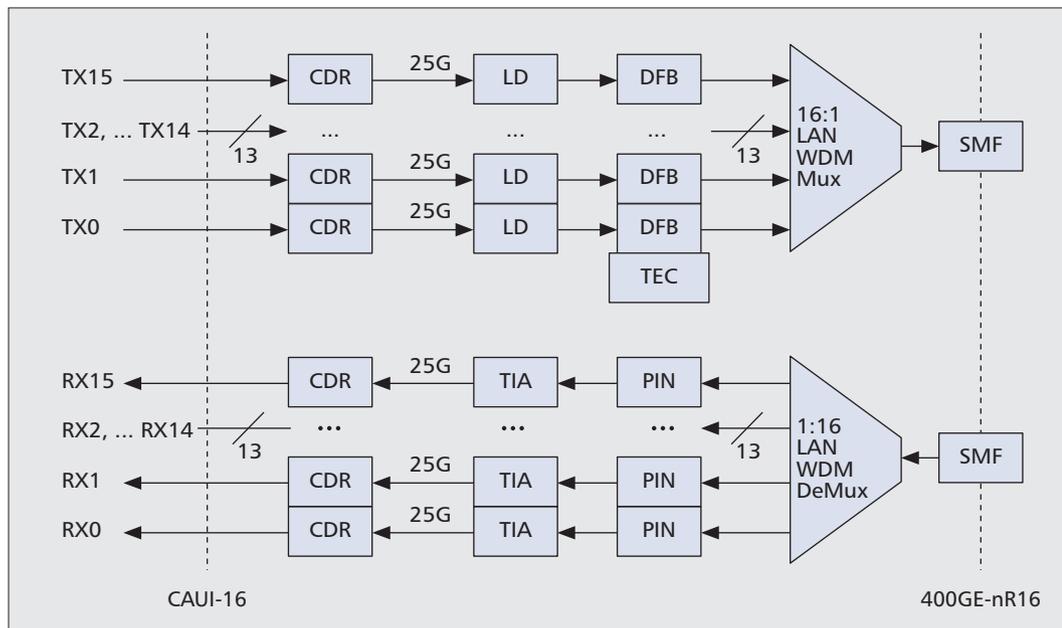


Figure 7. Proposed first-generation 400G structured data center duplex SMF optics.

increase and still not significant enough bandwidth increase to justify a huge R&D investment.

This differs from what happened after 10G when both 40G and 100G Ethernet standards were adopted in IEEE 802.3ba-2010. The 100G standard was defined first to meet the bandwidth demands of HPC, IDC, and CCO applications. The 40G standard was added afterward to support low-cost high-volume server interconnect applications. Had 40G been defined first, it is unlikely that 100G would have been defined as the next data rate. A more logical next standard would have been 160G. Such a step was under consideration by the ITU-T as the next Transport standard after 40G, until alignment with 100G Ethernet was determined to be more important.

The logical standard to consider after 400G is 1.6T. It is consistent with prior technology-driven $4 \times$ standard data rate increases. It is also the minimum bandwidth increase that justifies the huge required R&D investment.

TECHNOLOGY CONSIDERATIONS

A direct extension of 100G technology to 1.6T requires $64 \times 25\text{G}$ direct modulation lasers or 25G modulator-lasers. This is not practical

because of connector complexity, PCB routing, switch ASIC I/O, and cost limitations. Even PAM-4 requires $32 \times 25\text{G}$ lasers, which is still not practical due to the same limitations.

The only approach to control lane count beyond 1T Ethernet is higher order modulation. 100G Transport technology can be extended to client implementations, for example, by integrating 16 100G transmitter modulator-lasers. Use of more complex modulation would require integration of fewer transmitter modulator-lasers. This involves large optical component count PICs tightly coupled with CMOS digital signal processing (DSP) ASICs. Presently, no implementations exist that come within orders of magnitude of the cost, power and size requirements of client optics. A huge R&D investment is needed to develop such highly novel technologies.

CONCLUSIONS

At 100G and below, major client optics applications are high-density data center, structured data center, carrier central office, and general data center. They will continue as major applications beyond 100G. First-generation 100G client MMF and SMF optics are based on a mix of 10

Beyond 100G, 400G is the likely next standard based on historical, economic, technology and bandwidth growth considerations. 400G optics can be developed by extending 100G technology.

× 10G electrical lane and 10 × 10G or 4 × 25G optical lane architectures, and support reaches from less than 100 m to 40 km. They are deployed in HPC, IDC, and CCO high-end applications. Next-generation 100G MMF and SMF client optics will be based on 4 × 25G electrical lane and 4 × 25G optical lane architecture, enabling continued bandwidth growth and high-volume applications. Beyond 100G, 400G is the likely next standard based on historical, economic, technology, and bandwidth growth considerations. 400G optics can be developed by extending 100G technology. Beyond 400G, 1.6T is a possible standard, requiring huge R&D investment to develop highly novel technologies.

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