100 Gigabit Ethernet—Fundamentals, Trends, and Measurement Requirements

By Peter Winterling

Nearly every two years, a new hierarchy level is announced for telecommunications. The introduction of the 40 Gbps technology has dominated telecommunications for the last two years and now everyone is talking about 100 Gbps as the next generation. On the surface, everything looks simply like a change of generations is taking place and 40 Gbps seems to be outdated already. However, the introduction of 100 Gbps technology is quite different from the introduction of previous generations.

If we look at this more closely, the terms 40 Gbps and 100 Gbps are general terms for comprehensive technological changes in transmission technology. Particularly during this phase of implementing new technology, measurement technology plays an extraordinarily important role.

The transition from Gigabit Ethernet (GigE) to 10 GigE brought Ethernet technology to transport networks and, from the aspect of the transmission protocol, this represented a more important milestone than the introduction of the 100 GigE technology. The standardization is still not finalized; however, no significant changes relative to 10 GigE technologies are expected. Anything revolutionary will be determined by physical parameters. It was clear with the 40 Gbps technology that transmissions in existing transmission infrastructure are possible only with substantial modifications to the optically transmitted signal and path. Now, all possibilities must be exhausted for the transmission of 100 GigE (OTU4) in Wide Area Networks (WANs).

Standardization for 100 Gigabit Ethernet

Three organizations are involved in the standardization for 100 Gigabit Ethernet. IEEE's Higher Speed Study Group (HSSG) defines the Ethernet specifications under the term 802.3ba. At ITU-T, the SG15 standardization group deals with the integration of the 100 GigE and 40 GigE signals within the OTN framework. At OIF (Optical Internetworking Forum), the PLL (physical and link layer) work group is working on the integration of these signals in DWDM technology for Metro Area Networks (MANs) and WANs.

The initial position for the standardization of 100 GigE specified retaining the past frame sizes and frame formats of the IEEE 802.3 standard. For the MAC layer, the target was a transmission quality with a bit error rate of less than BER = 10^{-12}. Efforts would be made to use the OTN technology as a transport medium and to support it with corresponding specifications.

Table 1: Standardization for 40 GigE and 100 GigE

Physical Medium Device (PMD)	40 GigE	100 GigE
Multimode optical fiber < 100 m with OM3-fiber	40GBase-SR4: · Ribbon fibers · 850 nm · 4 x 10 Gbps	100GBase-SR10: · Ribbon fibers · 850 nm · 10 x 10 Gbps
Single mode optical fiber > 10 km	40 GBase-LR4: · CWDM 20 nm (Channel spacing) · 1310 nm · 4 Wavelengths x 10 Gbps	100GBase-LR4: · LAN-WDM 4.5 nm · 1310 nm · 4 Wavelengths x 25 Gbps
Single-mode optical fiber > 40 km		100GBase-ER4: · LAN-WDM 4.5 nm · 1310 nm · 4 Wavelengths x 25 Gbps
Single-mode optical fiber, not standardized		not standardized · Channel spacing 8 nm · 1550 nm · 10 Wavelengths x 10 Gbps

For now, 100 GigE is transmitted via several optical channels using the multi-lane concept. Three different physical interfaces are standardized — see Table 1. Two ranges are defined for transmission via a single-mode fiber:

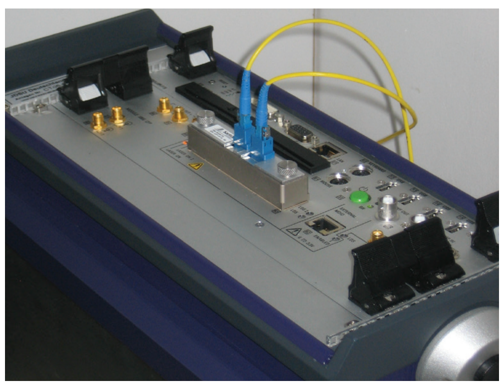

Figure 1. Viavi optical network tester with 100 GigE module and CFP

- 100GBase-LR4 (long range) describes the optical interface for four wavelengths within the range of 1310 nm with a channel spacing of 4.5 nm with an attainable transmission range of 10 km and 100GBase-ER4 (extended range) for a range of 40 km.
- For the first tests, yet another optical interface with 10 wavelengths in the 1550 nm range is available. This variant, which was not standardized, however, is technically the simpler solution since the multiplexers (“gearboxes”) can be omitted in these transponders.

For short connections within a computer center, another interface for multimode fibers is defined in the wavelength range of 850 nm. Here, ten transmission channels run parallel in a cable by means of ribbon fibers. The transmission channels are plugged together in an optical plug. By using OM-3-fibers, transmission lengths of at least 100 m can supposedly be achieved.

In addition to the optical interfaces, an electrical interface was also defined for both data transmission rates. Thus, a maximum transmission range of 10 m should be obtainable by four or ten parallel signals.

Acronyms

ASIC	Application Specific Integrated Circuit
BER	Bit Error Rate
CAUI	100 Gigabit Attachment Unit Interface
CD	Chromatic Dispersion
CFP	100 Gigabit Small Form Factor Plug-gable
CGMI	100 Gigabit Media Independent Interface
DFB	Distributed Feedback (Laser)
DWDM	Dense Wavelength Division Multiplex-ing
DQPSK	Differential Quaternary Phase Shift Keying
ER	Extended Range
FEC	Forward Error Correction
GigE	Gigabit Ethernet
GFP	Generic Frame Procedure
GMPLS	Generalized Multi-Protocol Label Switching
HSSG	Higher Speed Study Group of IEEE
IEEE	Institute of Electrical and Electronics Engineers
IrDI	Inter Domain Interface
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
LAN	Local Area Network
LR	Long Range
MAC	Medium Access Control
MDI	Media-Dependent Interface
MDIO	Management Data Input/Output
MII	Media-Independent Interface
MLD	Mult-Lane Distribution
MSA	Multi-Source Agreement
ODU	Optical Data Unit
OIF	Optical Internetworking Forum
OM3	Optical Multimode Class 3
OPU	Optical Payload Unit
OTL	Optical Channel Transport Lane
OTN	Optical Transport Network
OTU	Optical Transport Unit
PCS	Physical Coding Sublayer
PMD	Physical Medium Device
PMD	Polarization Mode Dispersion
PMA	Physical Medium Attachment
PLL	Physical and Link Layer
QoS	Quality of Service
SDH	Synchronous Digital Hierarchy
SFP	Small Form-Factor Pluggable
SG	Study Group
STM	Synchronous Transport Module
TK	Telecommunication
VC	Virtual Container
VCAT	Virtual Concatenation
VLAN	Virtual Local Area Network
XFP	10 Gigabit Small Form Factor Pluggable

The optical interfaces for transmitters and receivers are integrated in so-called CFP modules (100 Gigabit small-form-factor pluggable). Similar to the pluggable XFP modules (10 Gigabit small-form-factor pluggable), they are also transponders that can be changed during operation ("hot swappable") and that are independent of protocol. The four DFB lasers with their corresponding higher optical power output require efficient heat management for the CFP module. It is plugged into a precision shaft, its connection ensuring corresponding temperature heat dissipation. Figure 1 shows the Viavi Solutions ONT-503 optical network tester with the 100 GigE plug-in module. The CFP module is clearly visible. Figure 2 shows the OSI reference model as per IEEE 802.3ba for 100 Gigabit Ethernet.

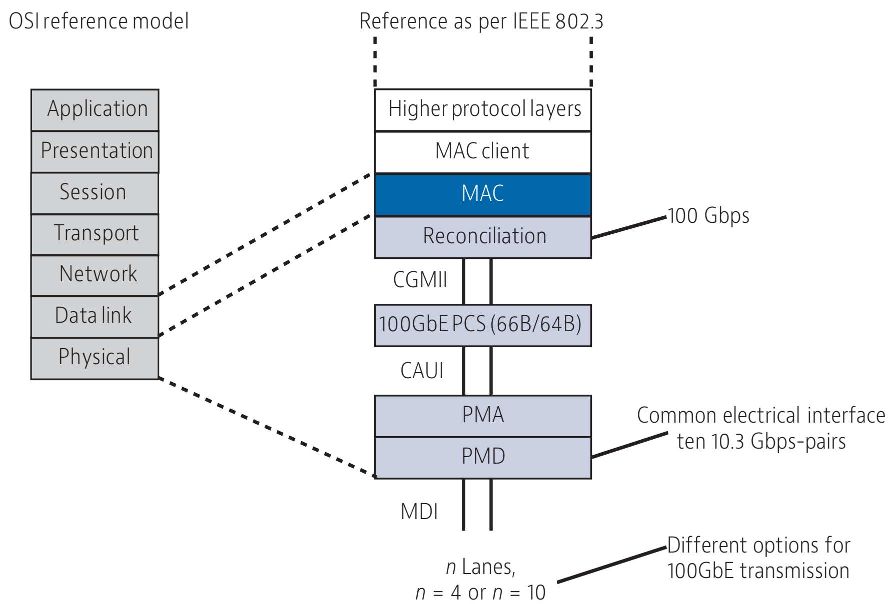

Figure 2. OSI reference model and Ethernet PHY reference model as per IEEE 802.3ba

Besides the optical transmitters and receivers, CFP modules also contain multiplexers/demultiplexers. Thus, the 20 virtual data streams, which are structured in 10 physically parallel data streams of 10 Gbps each, are combined by the MAC layer into four physical data streams of 25 Gbps each. Multiplexers and demultiplexers require space in the CFP module and contribute significantly to the temperature budget. Long term, these functions will migrate to the ASIC of signal processing. This requires an appropriate board layout and a connecting path for transferring to the optical interfaces for 25 Gbps or 28 Gbps in place of 10 Gbps. Therefore, the optical interfaces can end up being significantly smaller than today's CFP modules and the overall design becomes significantly less expensive. Possible names for it are CxFP and QSFP.

The interfaces and the management functions of this module are described in detail in the CFP MSA Management Interface Specification [1]. The CFP MSA defines a transceiver for 40 Gbps as well as for 100 Gbps, including its use for high-speed Ethernet (40 Gigabit and 100 Gigabit Ethernet). All efforts are directed towards the common agreement to develop a reasonably priced 100 Gbps technology. Optical transponders significantly affect the cost structure of the transmission system and thus the focus is on them.

For transmission in MANs and WANs, the 100 Gbps signal must be integrated into the OTN according to the ITU-T recommendation G.709. For 100 Gigabit Ethernet, an OTU4 framework is defined and the description of the physical interface for a transmission in four parallel channels was expanded accordingly [2]. The different variants are shown in Figure 3. The possibility of integrating other client signals in OTU4 is enabled explicitly.

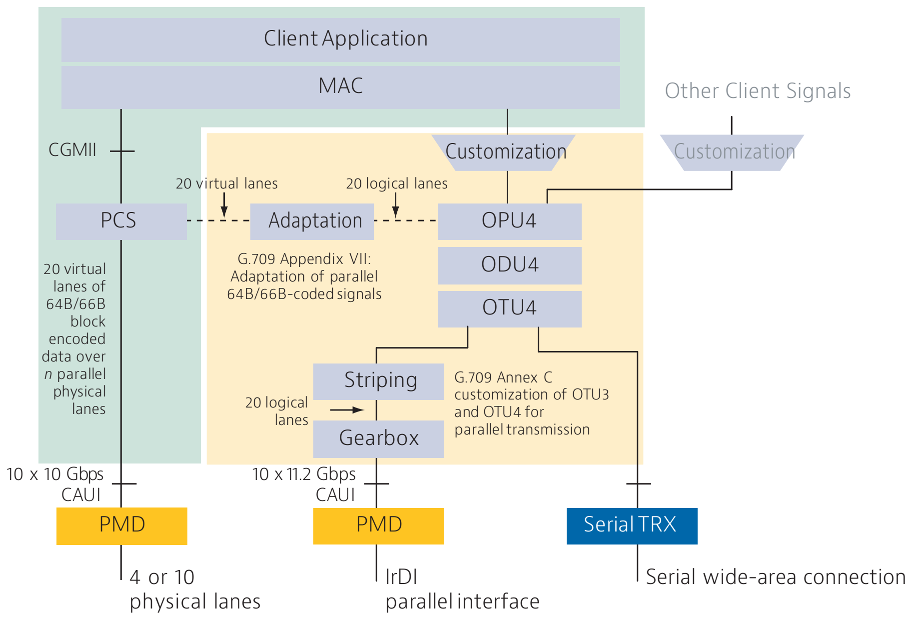

Figure 3. 100 GigE and OTN integration

With this first step of parallel transmission, an essential goal of increasing spectral efficiency in WANs has not yet been attained. Today, DWDM networks are primarily realized with a channel spacing of 50 GHz and with adequately high-level modulation procedures (for example, DQPSK), a 40 Gbps signal can already be transferred in a channel of the OTU3 framework [3]. With these admittedly very complex and accordingly expensive transponders, the transmission systems can bridge distances of more than 100 km. For quite some time, a well-known large network operator has been equipping its WAN with this technology.

With 100 Gbps becoming possible, the technical development of the transmission systems should make much more economical transponders available. Later, these transponders will enable serial transmission in a channel by means of higher modulation methods. Only then will it be possible to obtain a higher spectral efficiency. The CFP MSA explicitly describes the 40 GigE as an interface as well, which is likewise described in the 802.3ba IEEE standard Figure 1. However, significantly cheaper transponders are required for the 40 Gbps level, because 100 GigE does not replace this technology by any means. The balancing act of ever smaller optical transponders, which are still required to cope with large ranges of WANs having a high spectral efficiency, is not yet resolved and technical experts will ponder this problem for some time to come.

Test requirements for CFP modules for 100 Gbps

More than ever, the introduction of 100 GigE requires a measurement technology that has been customized appropriately in order to accompany the stage-by-stage introduction.

Manufacturers of components and systems require measurement engineering for 100 Gbps. For testing the CFP modules used in the transmission systems, a 100 GigE signal must be produced with ten parallel electrical connections that are coded as 20 virtual channels. The Ethernet signal coming from the MAC layer is not firmly allocated to the virtual channels. In accordance with the specification, the virtual channels on the transmitting end can be shifted as desired at the entry of the multiplexer. They are being sorted as per the so-called round-robin principle. The receiver must synchronize itself automatically. It must be possible to set any configuration at the time of the test. Figure 4 shows the adjustment possibilities on the transmitting end.

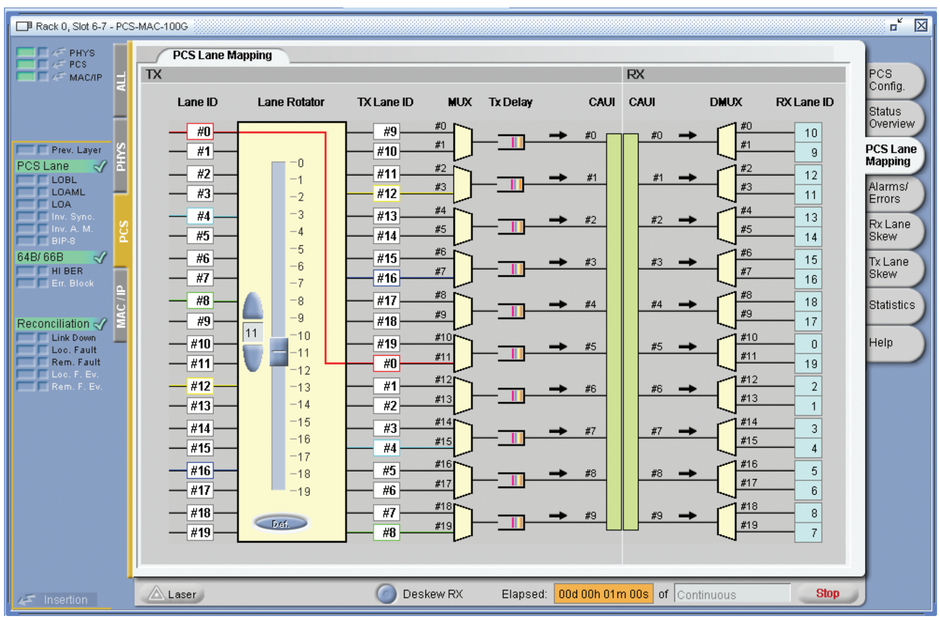

Figure 4. Multi-Lane-Distribution (MLD) tests for 40/100 GigE

At the optical interfaces of the CFP, the analyzer verifies the multiplex function and correspondingly tests the bit error rate of the client signal. The value of $BER = 10^{-12}$ must be adhered to, which is possible only by using forward error correction (FEC). This can be checked by displaying the bit errors in the PCS layer. The analyzer must, of course, make the optical parameters of its own CFP available over the MDIO management interface, as the information about the exact wavelength and the optical output levels should be known.

For IEEE-compliant CFPs, it is extremely important to test the skewing for each individual optical channel as well as the error-free acceptance on the receiver side. This is statically possible by inputting the number of bits to be moved in the individual physical channels; as per the 802.3ba IEEE recommendation, dynamic skewing is also described, which requires an external timing distribution method.

All these tests, which are required for 100 GigE because of the parallel transmission, are integral part of testing the function of CFP modules. Using one of the first CFPs commercially available from a reputable manufacturer, Viavi has shown its compliance with standards at the end of 2009.

Stressed receiver sensitivity for transponders

For SDH and OTN, the standardization for jitter measurements is given in the O.172 ITU-T recommendation. However, this cannot easily be adopted for package-oriented Ethernet transmissions. Therefore, the IEEE described a “Stressed Receiver Conformance Test” in the 802.3ae standard (chapter 52): A reference signal is changed with different parameters both in amplitude as well as in frequency, with the goal of simulating the transmission characteristics through a glass-fiber route as realistically as possible. The bit error rate is measured as a function of these parameters. Additionally, the eye diagram could be analyzed with a fast digital oscilloscope. For years, the Viavi Hydra testing system has been used to determine the stressed receiver sensitivity of 10 Gbps SFP modules for characterizing transponders. Figure 5 shows a solution for 100 GigE using the multi-lane concept. Optical modules contained in the MAP-200 measuring platform take over demultiplexing and multiplexing and select the parallel wavelength to be affected. In the transition mode of the Hydra testing system, the signal of a wavelength is controlled in accordance with the requirements of SRS testing. The ONT-503 network tester will send a 100 Gbps signal to the CFP module via the CAUI interface and determine the bit errors by means of the returned signal.

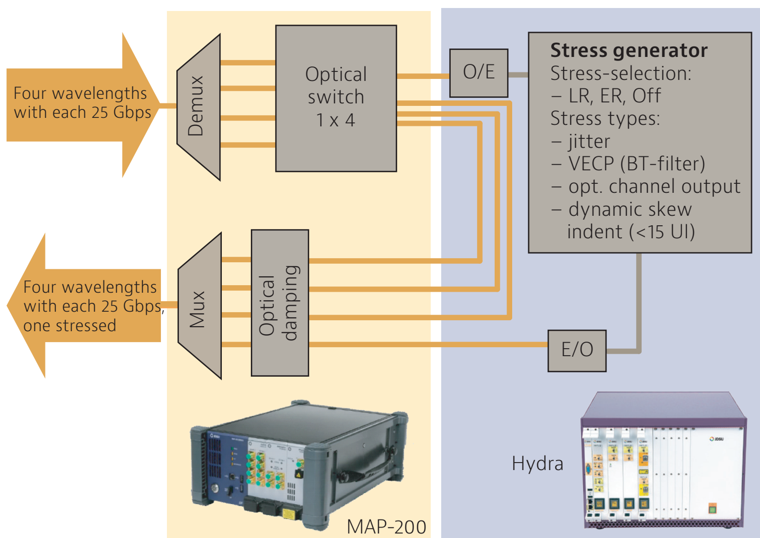

Figure 5. “Stressed eye testing” in case of four wavelengths with respectively 25 Gbps

Although the IEEE does not have a final standardization for the stressed receiver sensitivity measurement, Viavi has already presented a solution with a first approach for testing.

Line cards and interaction in the transmission system

Along with the described transponder tests, the complete test of network elements for 100 GigE also includes the validation of the PCS layers and an Ethernet IP protocol test that is as comprehensive as possible.

For this purpose, four (for 40 GigE) or ten (for 100 GigE) parallel interfaces must currently be adapted and analyzed in the MAC/IP layer. The configuration options and their evaluation do not differ from the analysis of 10 GigE. For example, it should therefore be possible to produce and analyze 256 independent streams with different traffic profiles. VLAN tagging, “MAC in MAC,” and GMPLS analysis are just as necessary as statistical evaluations regarding frame losses, latency, packet jitters, and service disruption, as shown in Figure 6. Basic tests, for example, are an extensive quality of service (QoS) analysis along with special test frameworks and a corresponding bandwidth evaluation (bandwidth utilization).

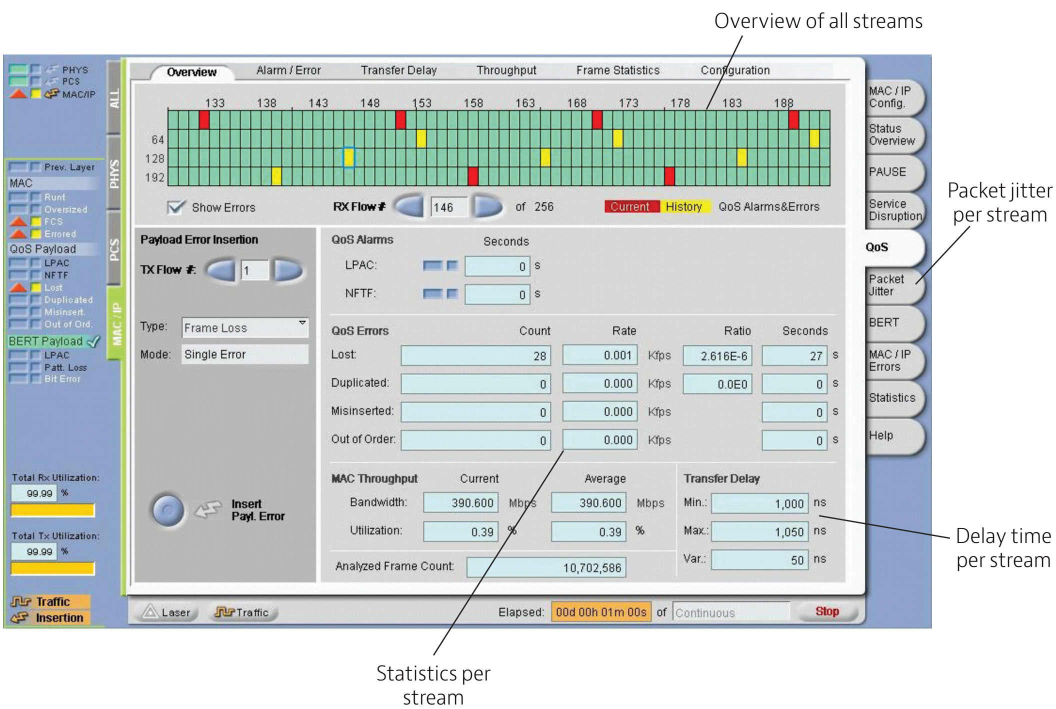

Figure 6. Complete Ethernet test depth with the tester ONT-503

The next step, the integration of the Ethernet signal within the OTU4 OTN- framework for transmission in MANs and WANs, Figure 4, first uses four parallel transmission paths. The nomenclature for such regenerated signals corresponds to OTL *k*. *n* (Optical Channel Transport Lane), wherein *k* stands for the hierarchy level and n for the number of wavelengths at the optical interface. For OTU4 with a bit rate of 112 Gbps and four wavelengths, the physical interface would then be OTL4.4; for OTU3 with 43 Gbps, it would be OTL3.4. Figure 7 shows the variants, which are tested accordingly.

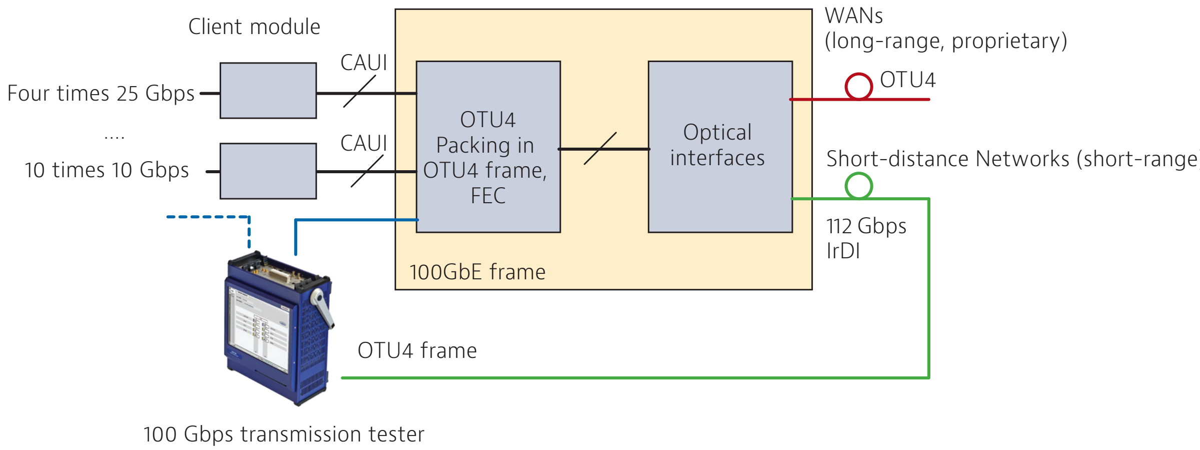

Figure 7. 100 GigE and OTN Interworking Test

Just as in low hierarchies, the wrapper or de-wrapper function is an important test in the OTN layer as well. The test examines whether or not the client signal is correctly mapped within the OTN frame and if the bits for the forward error correction were produced and if the output signal complies with the G.709 ITU-T recommendation and vice versa.

The test becomes significantly more complex if the client signal in one of the next steps is no longer exclusively an Ethernet signal. By means of the current ITU-T standardization, even ODU multiplexing is possible using lower hierarchies, for example, OTU3. In the OTN layer, the tester must map all the changes for G.709 as well. An extreme example is the concentration of 80 different ODU0 frames with one GigE signal each as a payload in an OTU4 frame [4]. Figure 8 shows the test variants and interfaces in a Netscape format.

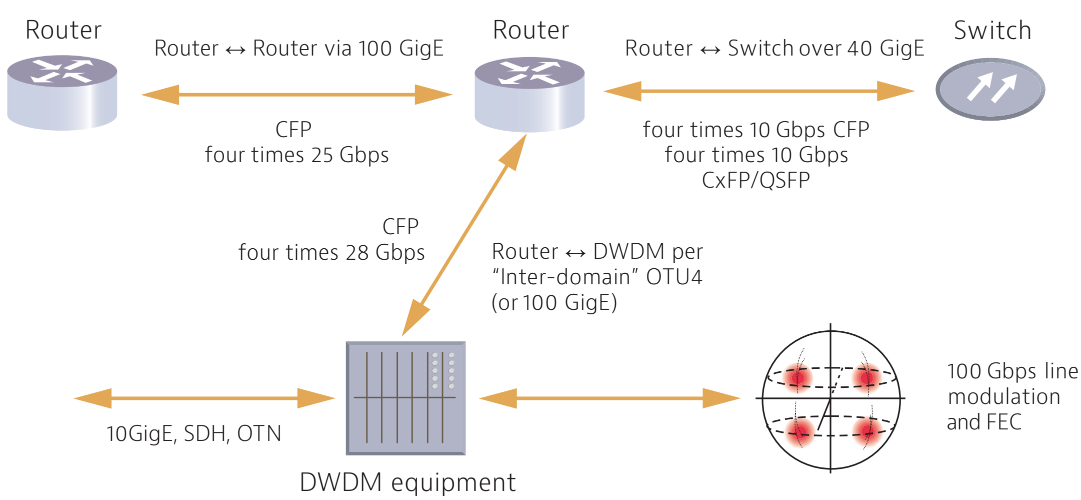

Figure 8. Interworking tests at 100-GigE and OTN layer

The multi-lane concept in the MAN and WAN

Up to now, a DWDM system transmission channel could be transferred with each wavelength using fixed channel spacing. A 40 Gbps signal can only be transmitted into the conventional 50 GHz channel spacing using high-level optical-modulation procedures [4]. This will not be different for the 100 Gbps technology; instead, more complex modulation procedures, for example the polarization multiplex, will be used. However, it is new that four wavelengths are required for the first step of the implementation of the 100 GigE for distances of up to 10 km (in MANs, therefore).

The Optical Internetworking Forum (OIF) is working on the integration of this multi-wavelength transmission system into the existing infrastructure. There are questions to be answered, such as how channel groups are to be organized in existing DWDM systems, how an equivalent network works, how this multi-lane concept is to be integrated in a network management system, etc. Apart from these structural questions, there are also additional physical hurdles, which are developing during transmission. Polarization mode dispersion (PMD) and chromatic dispersion (CD) are fiber characteristics that can severely limit the transmission range of signals with high bit rates.

Conventional systems are already compensating for static chromatic dispersion and the introduction of multi-lane systems raises the question about the acceptable tolerance for the compensation of all wavelengths of the DWDM system.

In contrast, PMD is changeable and depends on external influences such as changes of temperature and the mechanical load of the fiber. An example of this is the vibration in guard wires of high-voltage transmission lines of integrated fibers or cables over bridges and in underground shafts. Since PMD varies not only over time but also with different wavelengths, it requires special attention in the case of multi-lane systems.

The average value of PMD as a function of wavelength is determined by using the measurement procedure common today for fiber characterization after the installation of the cable. In the case of a single-channel system, the maximum limiting value of the dispersion is calculated by the degradation of the quality of service (QoS) of 1 dB (10 ps for 10 Gbps systems, for example). Additional criteria must be found for multi-lane systems. The use of coherent optical receivers with subsequent digital signal processing considerably diffuses the dispersion issue. It is questionable whether this still-expensive technology is already being used in multi-lane concepts or if it will be reserved for the future serial transmission of OTU4 with only one wavelength.

100 GigE still has a long way to go

In contrast to all other earlier generation steps, the 100 Gbps technology is being realized for the first time for short transmission paths and first will be applied in computer centers for networking powerful computers. Interfaces defined for ranges of 10 km and 40 km will first be geared for use in the MAN. But whether in computer centers or in the MAN, 100 Gbps technology will be introduced with parallel transmission and for that to happen, a workable concept is required for the integration of a multi-lane system into the existing optical DWDM networks. In the next generation, it will be possible to use 100 Gbps for serial transmissions. However, many development steps are necessary in order to achieve these goals. These include the cost-effective implementation of higher-level optical-modulation procedures (including polarization multiplexing) and the realization of fast signal processors to smooth the way for coherent receivers.

And, sophisticated measurement equipment and techniques will be necessary to accompany this development. Basic equipment must support all interfaces for the SDH and OTN hierarchy, from STM-1 to OTU4 and now also 10 GigE and 100 GigE.

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