High Speed Ethernet Backhaul

White Paper

AimValley

Achieving high speed performance in no-time!

The volume of traffic being transported on the world's telecom networks has been rising exponentially for decades. In recent years streaming video has, by far, become the largest portion of the traffic and overall traffic is now almost exclusively Ethernet packets, with video, voice, data, control messages, and machine to machine communications being encoded into packet streams. In terms of the physical build out of telecom networks, fiber optic cable is used for the vast majority of long haul transport and it is also used for most metropolitan networks, most cell tower backhaul connections, most corporate enterprise connections, and more and more is becoming the physical media to connect homes.

To accommodate the ever-rising amount of transported data, telecom service providers have continuously added additional fiber. Equally important is that technology has continued to evolve such that transmission rates (bits per second) hav increased in several orders of magnitudes. Not that many years ago a Gigabit per second was the highest transmission rate, the current state of the art in practical deployment is 800 G and Terabit per second rates are on the horizon. Of course, the advantage provided through upgrades of transport gear to carry far higher bit rates is the elimination of the need to install new fibers. That is especially important in long and medium haul fiber routes where the physical construction work across hundreds of kms is both expensive and time consuming.

Signal processing is done in the electrical domain while transport takes place in the optical domain. So a need exists for conversion.

The predominant transport technology used is Ethernet over optical transport using wavelength division multi-plexing (WDM, DWDM) and higher order modulation techniques such as Phase & Amplitude Modulation with 4 states, in other words PAM-4. Common rates are 1, 10, 25, 50, 100, 400, 800 Gigabits per second and soon Terabits per second, TB/s.

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Evolution of Optical Transport Modules

There are many (front panel pluggable) optical modules available offering the electrical/optical conversion.

GBIC: the first pluggable module was developed in 1995 supporting for 1G Ethernet and 2.5G SDH/SONET and 4G Fiber Channel (FC).

XENPAK: this module followed around 2001 and the predecessors XPAK, X2 and XFP, which supported 10G Ethernet, FC, SONET, SDH & OTN.

CFP Family: around 2013 the CFP family started. Originally developed for 100G Ethernet, SONET/ SDH/OTN. Today also 200 and 400 Gbps trans-mission speeds are supported using advanced modulation technology e.g.

- Dual Polarization Quadrature Phase Shift Keying (DP-QPSK)
- Dual Polarization Quadrature Amplitude Modulation (DP-8QAM/DP-16QAM)
- Probabilistic Constellation Shaping Quadrature Amplitude Modulation (PCS-16QAM)

Also other functions are integrated a.o forward error correction methods, extended C-band, polarization diversity coherent detection and advanced electronic link equalization.

Specifications	CFP	CFP2	CFP4	CFP8
Dimension [mm] WxHxD	82 x 13.6 x 144.8	41.5 x 12.4 x 107.5	21.5 x 9.5 x 92	40 x 9.5 x 102
Nr. pins in electrical connection	148	104	56	124
Digital Signal Processing (DSP)	Integrated	None	None	None
Max. power consumption [W]	24	12	6	24
Number of lanes	10x 10G, 4x 25G	10x 19G, 4x 25G, 8x 25G, 8x 50G	4x 10G, 4x 25G	16x 25G, 8x 50G

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Additional Pluggable Optics Modules

Commonly used are SFP, QSFP and OSFP families of pluggable optics. Compared to the CFP family these devices offers less advanced functions. There is no clock data recovery, no elastic storing or buffering, simpler electrical interfaces that support fewer pins, lower available power budget and smaller dimensions. See table below for more details.

Name	Year	Rate	Details	MSA Max Power
SFP	2001	1Gbs	Small form factor pluggable up to 1Gb. Designed for Gigabit Ethernet, 2.5 Gbps SDH/SONET and 4 Gbps Fiber Channel.	1
SFP+	2009	10Gbs	Fiber optic transceiver for 10 Gb. Designed for 10Gbs. Supports 8Gb/s Fiber Channel, 10 Gbs Ethernet and OTN standard OTU2	1.5
SFP28	2014	25Gbs	Fiber optic transceiver for 25 Gb	
QSFP	2006	4Gbs	Quad Small Form-factor Pluggable, 4 lanes SFP	2.5
QSFP+	2012	40Gbs	4 lanes SFP+. Supports Ethernet, Fiber Channel, InfiniBand and SONET/SDH standards up to 40GB/s and 100Gb/s	3.5
QSFP28	2014	100Gbs	4 Lanes SFP28	
QSFP56	2015	200Gbs	Like QSPF28 and PAM4 lincoding	
QSFP-DD	2016	400Gbs	Like QSFP56 with doubling the number of lanes to 8	12
QSFP112	2021	400Gbs	Like QSP56 with doubling the symbol rate	
QSFP-DD800	2021	800Gbs	Like QSFP112 with doubling the number of lanes to 8	
OSFP	2021	400Gbs	8 lanes (Octal). The OSFP has an integrated heat-sink that greatly improves thermal performance and enables modules with up to 15W power in a switch chassis with conventional airflow	15

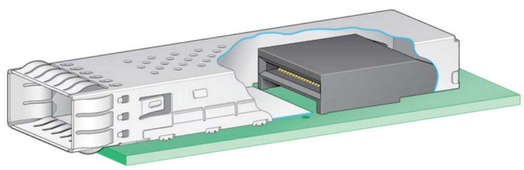


Figure 2: QSFP recepticle

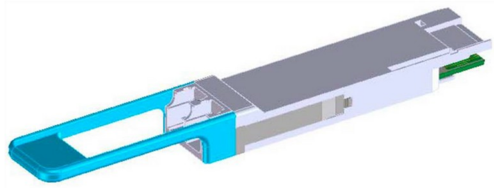
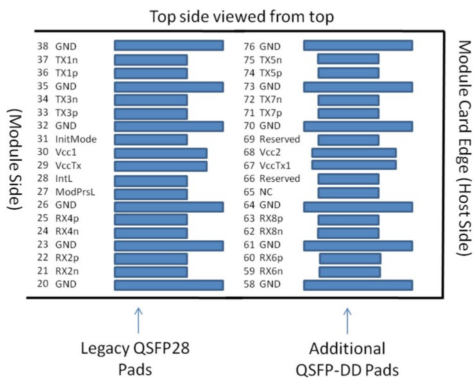
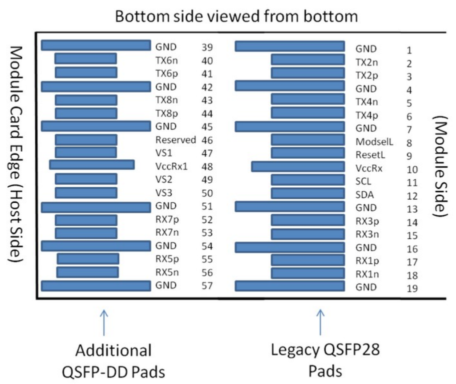


Figure 3: QSFP Optical Module





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Bandwidth and noise constraints

Wavelength are used to carry signals over fiber optic cables but at some point the data is converted to electronics in Optical Packet switch, or router. High speed electronics are used to convert the signals and process the packets. As speeds increase even the shortest amount of electrical signals can be affected by bandwidth and noise constraints. Several measures are required. There is large number of techniques and FPGA code sources supporting many existing transmission concepts and new adaptions.

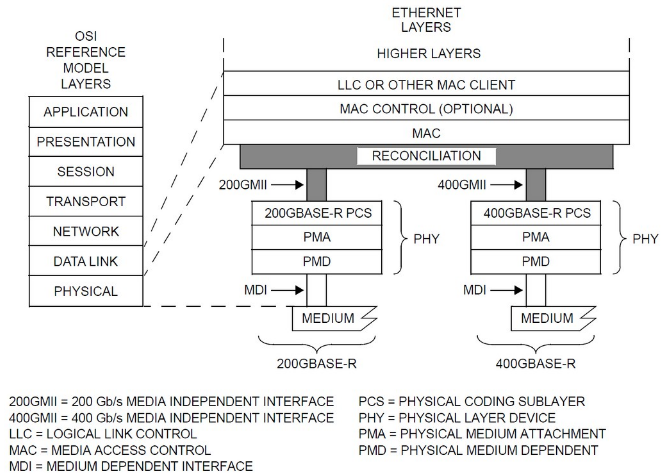
Listed below are is an overview of the most important measures, leaving out specific parameters and possible choices.

Spread the traffic

Traffic can be spread over multiple lanes. A lane can be an electrical balanced circuit between two end-points mapped to a specific optical wavelength e.g. CWDM. Lanes can also be combined and transmitted in the optical domain using coherent modulation technique.

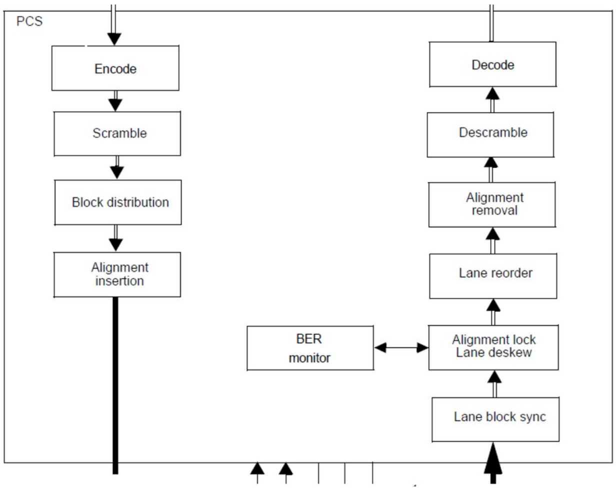
For high speeds alignment markers/codes are needed. These are added in the PCS layer at the transmitting end and processed at the receiving end, to find the correct relation.

It is well known that stringent timing relations (also known as skew) exist between the lanes. The actual relatively straightforward lane (de)multiplexing takes place in the PMA layer.



Scrambling

Scrambling eliminates the dependence of a customer signal's power spectrum upon the actual transmitted data. Most scrambling techniques are self-synchronizing and always behave predictable without the need of a secret. Scrambling also helps to control the Power Spectral Density (PSD).



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Line encoding

Line encoding decouples the actual transmitted data from the applied signal on the physical media. There are many things to consider.

- **Embedded clock**, it is impractical to provide a separate timing circuit between a transmitter and a receiver to maintain synchronization. Since timing is absolutely critical for the reliable transmission at high signaling rates, the timing information must be embedded in the signal itself so that the receiver can extract the clock signal from the incoming bit stream.
- **Avoid low frequencies**, if the data to be sent includes long strings of ones or zeros, a zero-frequency DC component can develop in the electrical transmitted signal. This leads to signal distortion at the receiver, especially if transmission elements are AC coupled, not only the DC part of the signal will be blocked by transformers and capacitors but also energy is wasted.
- **Power efficiency**, the transmitted signal power should be as low as possible for the required data rate and probability of error in order to make the most efficient use of power and minimize the amount of electromagnetic noise on the transmission line
- **Target spectral density,** the Power Spectral Density (PSD) is the distribution of power over the frequencies that make up the signal.
  The PSD of the transmitted signal should be compatible with the communication channel's frequency response. If the signal bandwidth (i.e. the frequency interval that contains most of the signal's power) is greater than that of the channel, the higher frequencies will be cut off, causing the signal to spread out in the time domain. This phenomenon is known as *pulse-spreading*, and can cause *Inter Symbol Interference* (ISI). This makes it difficult for the receiver to decode the incoming signal correctly.
- **Interference**, if the power is concentrated in a narrow frequency band, it can interfere with adjacent channels or symbols also known as inter/cross-modulation. The interfering signals are independent but they cannot be individually extracted without performance (bit error rate) impact, due to non-linearity aspects.
- **Avoidance of baseline wander**, the average signal-power at the receiver is used as a base-line reference against which the value of incoming data elements is determined.
  The baseline value may drift up or down over time if long strings of ones or zeros are transmitted, making it difficult for the receiver to decode the incoming signal correctly.
- **Noise tolerance**, the degree to which noise is a problem depends on the type of transmission medium over which the signal is being sent. Some line coding schemes are inherently more tolerant of noise than others and thus present a better choice in noisy environments. Baseline wander can also have an adverse effect on noise tolerance, as it can cause the receiver's detection threshold to drift closer to the noise floor
- **Error detection and correction**, some line coding schemes have build-in (limited) error detection and correction capabilities.
- **Signal Allowance** for link level signal monitoring and alarming
- **Control symbols** are defined using combinations not used for user data, this allows for link level parameter exchange (auto-negotiation).
- **Level of complexity**, complex line coding schemes require sophisticated and costly electronic circuitry in the transmitter to encode the digital data for transmission and in the receiver to decode the incoming signal running at very high speeds.

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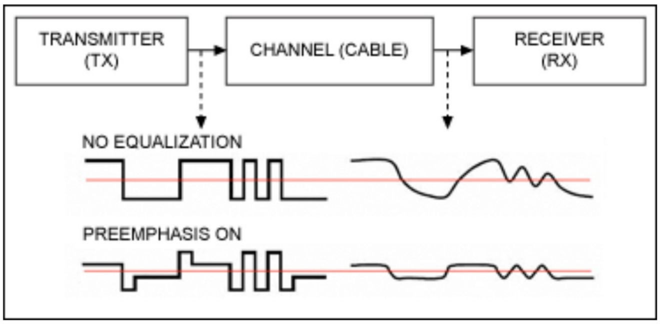
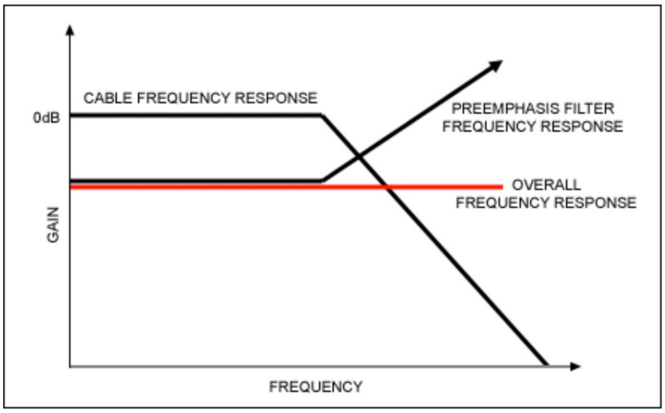
Pulse Shape

Applying pre-emhasis at the transmitting end and equalization at the receiving end helps to maintain the waveform.

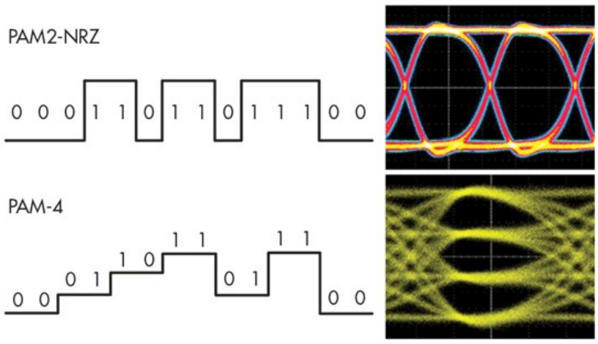




Information Density

The information density can be increased (bits) per symbol (baud).

As shown the penalty of using more signal levels is that multiple and smaller 'eyes' which lowers the signal to noise ratio by a third. In the middle of an eye the change for make a wrong data sampling error is the lowest. The bigger the eye the better.



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Forward Error Correction (FEC)

FEC enables the detection and correction of bit errors caused by physical impairments in the transmission medium. These impairments are categorized into linear effects e.g. attenuation, noise, and dispersion and nonlinear for example cross-talk. Noise can also be categorized, see below table for an overview.

By using FEC in a network link, the network operator can accept a lower quality signal in the link to correct potential errors. The applied RS(544,514), can compensate to a certain extend, the attenuation affects even though the data rate has increased slightly, see table below.

As a rule of thumb for each fiber connector or splice about 0.3 DB must be taken while for single mode fiber about 0.4 DB must be take per km (depending fiber type and wavelength).

FEC encoding	RS(544,514,t=15,m=10)	
Symbols including FEC overhead	544	
Message only symbols	514	
FEC overhead symbols	30	
Impact on message length	+5.8%	
Bits per symbol	10	
Correction symbols	15	
Detectable symbol errors	30	
Coding gain, give a Bit Error Rate (BER)	Burst	5.4 DB @ $BER=10^{-15}$
	Random	6.5 DB @ $BER=10^{-12}$

Next to the aforementioned hard decision (e.g. RS-FEC), soft decision FECs exists. A hard decision FEC takes at the receiving end binary conclusions while a soft decision (SD) FEC uses additional data bits to provide a finer, more granular indication of the incoming signal. The decoder provides a confidence factor. This results in an additional attenuation of 1–2 dB compared to hard decision FEC.

Year	Lanes*	Line Code	Modulation (levels)	Symbol Rate/ Baud Rate [GHz]	Relative Signal to Noise Ratio	Bandwidth (BW)	FEC	Acc. Line Rate	Module	Reach (Optical)
2010	10	64B/ 66B	NRZ (2)	10.3125	A	SR	–	103.125	QSFP+	WDM
2014	4	256B/ 257B	PAM4 (4)	25.78125	A/3	1/3 SR	RS (528,514)	103.125	QSFP28	WDM
2018	2	256B/ 257B	PAM4 (4)	26.5625	A/3	1/3 SR	RS (544,514)	106.25	QSFP28	WDM
2021	1	256B/ 257B	PAM4 (4)	53.125	A/3	1/3 SR	RS (544,514)	106.25	QSFP56	WDM
2022	4	256B/ 257B	NRZ (2)	25.78125	A	SR	SC-FEC	27.9525	QSFP28	Coherent DP-DQPSK

*Lanes per direction

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Coherent Transmission
Attenuation is the reduction of amplitude of a signal. For fiber optics, this includes connection points, splice losses, passive optical filters/splitters/couplers/ROADMs, etc., micro and macro bends and the inherent loss of fiber.

To compensate for fiber attenuation, coherent transceivers are able to automatically tune their output wavelength, as well as their output power.
Chromatic dispersion is the distortion of optical signals due to the variation of the speed of light at different wavelengths across the length of a fiber cable. Polarization dispersion is a drift in the orientation of light signals as it traverses a fiber optic path due to variations between the horizontal and vertical signal paths and twists and anomalies in the glass composition itself. Both chromatic and polarization dispersion are addressed by integrated Digital Signal Processors (DSPs) that compensate for these factors for the sake of signal reconstruction.

Speed processing
Processing high-speed Ethernet involves the use of high-speed SERDES technology. SERDES or Serializer/ Deserializer is a pair of functional blocks commonly used in high speed communications to compensate for limited input/output. These functional logic blocks convert data from serial data to parallel interfaces in two directions. In addition, high speed processing capabilities is required to process the parallel "blocks" as they arrive or as they are assembled. The internal processing clock rate as used by state-of-the-art ASIC/FPGA devices is limited to an upper limitation in frequency (typically well into the GHz range) GHz due to dissipation and signal integrity reasons. Although the rate of processing of the parallel blocks is much lower that the serial data rate, it does however create the need for extremely wide internal bus structures in the order of 1024 lanes, processed by highly optimized and complex pipelines.

Consideration Aspects:
- Frame alignment,
- Throughput,
- Efficient use of resources,
- Timing
- Synchronization

Note that during a single clock cycle multiple frame fragments may have to be processed.

Transport of high-speed Ethernet
The mature Optical Transport Network (OTN) technology is often used to carry (high-speed) client signals over long distances. OTN has been standardized by the ITU-T and defined in G.709. OTN Supports a wide range of client signals, starting from 1 Gbps to 100 Gbps and more. Also Packet and Constant Bitrate (CBR) signal t ypes can be carried. OTN supports sophisticated monitoring and diagnostic features.
For example: it is required when crossing operator domains and to support high availability services.

Given the increased need for speed, also the OTN standard required enhancement, known as "beyond 100G" (B100G) optical transport. Till recent the highest Optical Transport Unit was OTU4 which runs at 111.81 Gbps. With the focus on supporting today's and future high-speed Ethernet client signals this is clearly insufficient.

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The ITU-T and IEEE are working closely together to achieve optimal high-speed transport solutions. It considers physical layer aspects and also efficient mapping and flexible bandwidth allocation. Using OTUCn with a capacity of as n times 100 Gbps; e.g. n=8 to carry 800G Ethernet. The FlexO group carries a OTUCn signal over bonded 200G Base-R or 400G Base-R pluggable optical modules. The nominal FlexO bit rate is 105.643510782 Gbps, so slightly higher then the carried 100G signal which is needed to support OTN overhead and lane alignment information.

AimValley High-Speed Ethernet Backhaul Expertise

- Development of high-speed 100+ Ethernet interfaces applied in testing equipment.
- 100G Ethernet switch designs.
- Experience in applying high-speed FPGA transceivers.
- FPGA level high-speed frame processing.
- High-speed designs achieving the best possible signal integrity including analog simulation technology.
- Development of OTN transport and multiplex systems.
- Architecture and design of clocking and synchronization solutions at network, system, PCB or device level, incl. PLL and gearbox designs.
- Experience in creating time, frequency and delay critical solutions.
- Design and architecture of Ultra Low Latency solutions.
- Development of LIU front-end technology.

AimValley proven track record

- 800G Gearbox Mezzanine Board
- 400G FPGA PCIe Card
- 400G-800G Transmission
- Ultra Low Latency
- Synchronization

Why AimValley?

AimValley is a reliable provider of ultra high speed Ethernet backhaul technology since 2003, delivering solutions for:

- High speed data processing applications
- Complex FPGA-based accelerated systems
- High speed, low power hardware equipment
- Robust embedded software
- Early adopter of Acceleration Technology

AimValley understands the full complexities as well as the subtle nuances of designing great edge solutions. We excel in building complex systems that are part of your product in the fields of Industry 4.0, Big Data, Healthcare and Transportation markets. Our combined skills represent all the important aspects required for the development of end-to-end systems.

Our customers enjoy the benefits of working with a strong team with over 2000 years engineering experience. AimValley is a trusted partner of Tier 1 customers in Telecom and Industrial markets and has shipped more than 100 000 products.

Quality Focus

- Outstanding track record of on-time delivery
- Best in Class Designs – Time, Budget & Quality
- ISO9001, ISO140001, EcoVadis Platinum CSR

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