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Title: Supplement to ITU-T G-series Recommendations PON transmission technologies above 10 Gb/s per wavelength

Purpose: Admin

Contact: DeZhi (James) Zhang
China Telecom
China
Email: zhangdz@sttri.com.cn

Contact: Dekun Liu
Huawei
China
Email: liudekun@huawei.com

Contact: Yong Guo
ZTE
China
Email: guo.yong3@zte.com.cn

~~**Contact:**~~ ~~Frank Effenberger~~
~~Futurewei~~
~~USA~~
~~Tel:~~
~~Fax:~~
~~Email: frank.effenberger@huawei.com~~

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Abstract: describes characteristics of optical transmission above 10 Gb/s per wavelength between the optical line termination (OLT) and the optical network unit (ONU).

[Editors' note]: Include the agreed contribution on content frame and modulation technologies in telephone meetings to the draft;

Supplement to ITU-T G-series Recommendations PON transmission technologies above 10 Gb/s per wavelength

Contents

1 Scope

[Ed Note: This scope comes from the text agreed in Geneva meeting Sep 2016]

This supplement describes characteristics of optical transmission above 10 Gb/s per wavelength between the optical line termination **(**OLT) and the optical network unit (ONU). It reviews challenges of transmission above 10 Gb/s in optical access. A set of assumed system requirements is developed and candidate technologies are evaluated against these requirements. Some aspects considered include signal modulation selection, optical transmitter design, optical receiver design, and wavelength dependency. Coexistence with other optical access systems is also investigated as a key factor of wavelength planning.

2 References

[Ed Note: These reference come from the contribution 170124_D3]

[1] G. Agrawal, P. Anthony, T. Shen, “Dispersion penalty for 1.3-µm Lightwave systems with multimode semiconductor lasers,” J. Lightwave Technology, volume 6, number 5, 1988

[2] “Fiber communication system”, Beijing university of posts and telecommunications publishing Group, p. 183.

[3] Broadband Optical Access Networks , L. Kazovsky et. al. 2011.

[4] A. Lender, “The Duobinary Techniques for High-Speed Data Transmission,” IEEE Trans. Consumer Electronics, vol. CE-82, pp. 214–218, May 1963.

[5] Sinsky et al., “High-Speed Electrical Backplane Transmission Using Duobinary Signaling,” IEEE Transactions on Microwave Theory and Techniques, vol. 53, no. 1, January 2005, p.152.

[6] H. Shankar, “Duobinary modulation for optical systems,” White Paper, Inphi Corporation, (2004).

[7] Winzer P, Essiambre R. Advanced modulation formats for high-capacity optical transport networks [J]. Journal of Lightwave Technology, 2006, 24: 4711-4728

[8] G. P. Agrawal and N. K. Dutta, Long-Wavelength Semiconductor Lasers. New York: Van Nostrand Reinhold, 1986.

[9] T. Yamamoto, "High-speed directly modulated lasers," OFC/NFOEC, Los Angeles

[10] P. Ghelfi, A. Bogoni and L. Poti, "Numerical model of the dynamic absorption variation in QW-EAM for ultrafast all-optical signal" IEEE Proc.-Circuits Devices Syst., vol. 150, pp 512-515, 2003.

3 Definitions

To be added

4 Abbreviations and acronyms

To be added

5 Requirements

[Ed Note: In this section, propose to discuss the requirements]

6 System architectures

[Ed Note: In this section, propose to discuss feasible system architectures supporting above 10 Gb/s per wavelength, both single wavelength architecture and multi wavelength architecture.]

7 Candidate technologies above 10 Gb/s per wavelength

[Ed Note: In this section, propose to discuss all the possibilities and their impacts when enabling above 10 Gb/s per wavelength, including feasible optical technologies and modulation technologies such as NRZ, electronic duo binary, optical duo binary, PAM4 etc.]

7.1 Modulation technologies

[ED note: per agreement in Jan 24 meeting, contribution 170124_D3 is used as a baseline text]

7.1.1 NRZ modulation

7.1.1.1 NRZ modulation in O-band

NRZ modulation is the simplest and lowest cost way to transmit data over optical fiber. At 10Gb/s, directly modulated lasers (DML) are adequate in O-band for 20km transmission, but in long wavelength band, such as in S-band, C-band and L-band, electronic-absorption modulated lasers (EML) are necessary due to the dispersion limitation.

As bit rates increase up to above 10Gb/s, mitigation of increased chromatic dispersion is required. The dispersion tolerance (@1 dB dispersion penalty) for 25 GB/s and 40 Gb/s using EML transmitters (using the model in [1]), and the corresponding usable spectrum in ITU-T G.652 fibers (20 km length) without dispersion compensation (DC) is shown in Table 7.1-1.

Table 7.1-1: NRZ usable spectrum

NRZ bit rate	Dispersion tolerance (EML)	Usable spectrum (20 km, no DC)
10 Gb/s	1000 ps/nm	All of O-, E-, S, C, and L bands
25 Gb/s	190 ps/nm	1260−1410 nm
40 Gb/s	75 ps/nm	1290−1340 nm

In full O-band, due to the chromatic dispersion coefficient is very small, 25Gb/s EML laser with NRZ modulation can support 20km fiber transmission. In the zero dispersion wavelength range (near 1310nm) and O minus band (small negative dispersion), even the 25Gb/s directly-modulated distributed-feedback (DFB) lasers with NRZ can be used for 20km transmission.

If the wavelength spectrum could be limited to the spectrum between 1290-1330nm for a typical G.652 fiber with zero dispersion wavelength locates at 1310nm, then even 40Gb/s NRZ transmission for EML laser without dispersion compensation is viable. Of course, if we consider the worst case, which the zero dispersion wavelength of fiber may locate randomly between 1300nm~1324nm, the usable wavelength band will be much smaller.

[Editors'note based on 170426_D52]

The chromatic dispersion coefficient of G.652 fiber in O band is determined by Eq 7.1-1 and is shown in figure 7.1-1.

$$\frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\max}}{\lambda}\right)^4\right] \le D(\lambda) \le \frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\min}}{\lambda}\right)^4\right] \qquad (7.1\text{-}1)$$

where $S_{0\max} = 0.092\, ps/(nm^2 * km)$, $\lambda_{0\max} = 1324nm$, $\lambda_{0\min} = 1300nm$

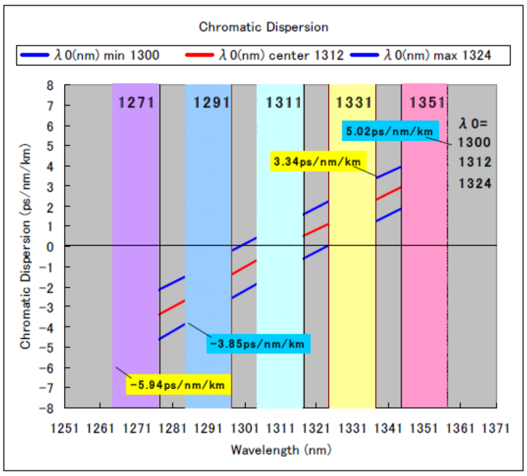

Figure 7.1-1. Chromatic Dispersion Coefficient of G.652 fiber in O-band

Based on Eq 7.1-1,for G.652 fiber in O-band , the minimal chromatic dispersion is -6.35ps/(nm*km) at 1260nm, the maximal chromatic dispersion is 5.17ps/(nm*km) at 1360nm.

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Based on the rate equation model of semiconductor lasers[8] and the parameters shown in[9][10] , Figure 7.1-2 shows the simulated eye diagram of 25Gb/s and 40Gb/s EML laser with NRZ modulation. From the figure, both 25Gb/s and 40Gb/s have very good eye diagram, which means the EML laser has enough bandwidth to support both 25Gb/s and 40Gb/s bandwidth.

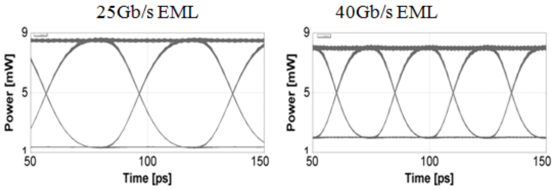

Figure 7.1-2 Simulated Eye diagram of EML laser with 25Gb/s and 40G NRZ modulation

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In Figure 7.1-3, ~~compares~~ the dispersion penalty after 20km based on the nonlinear Schrodinger (NLS) equation theory is compared with VPIphotonics fiber optics simulation tool. The chirp factor of EML is assumed as 0.5 [10], which is one typical value for EML laser.

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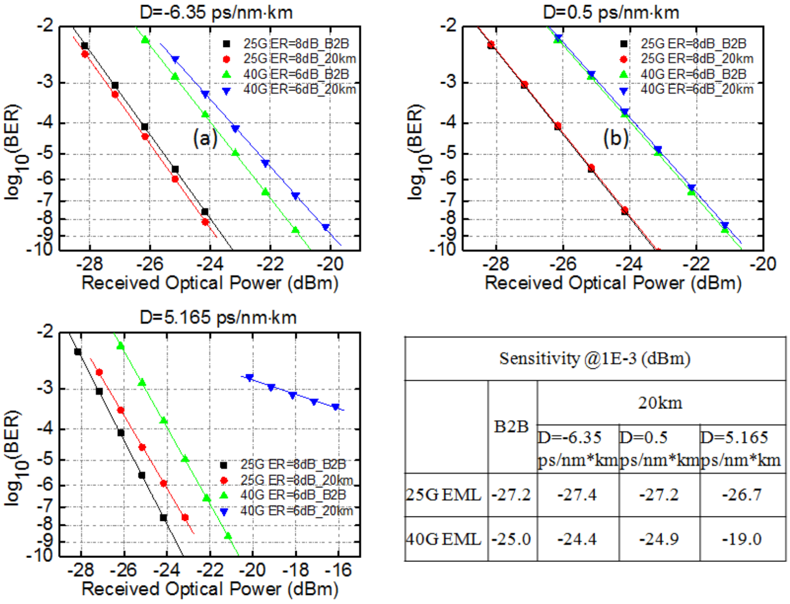

		Sensitivity @1E-3 (dBm)		
	B2B	20km		
		D=-6.35 ps/nm*km	D=0.5 ps/nm*km	D=5.165 ps/nm*km
25G EML	-27.2	-27.4	-27.2	-26.7
40G EML	-25.0	-24.4	-24.9	-19.0

Figure 7.1-3 25Gb/s and 40Gb/s EML dispersion penalty comparison after 20km (a) in O- band, (b) in zero dispersion band and (c) in O+ band

At back to back, there is ~2.2dB sensitivity difference between 25Gb/s and 40Gb/s EML. In O-band, due to the chromatic dispersion coefficient is negative, the sensitivity after 20km is even better compared with B2B by a little bit for 25Gb/s, for 40Gb/s due to the negative dispersion is too much, so there is a little penalty after 20km. In zero dispersion band, the dispersion penalty is negligible for both 25Gb/s and 40Gb/s. At O+ band, the dispersion penalty is still small, round about 0.5dB for 25Gb/s, while for 40Gb/s EML, the dispersion penalty becomes quite serious.

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Figure 7.1-4 shows the simulated eye diagram of 25Gb/s and 40Gb/s DML laser, and figure 7.1-5 shows the dispersion penalty after 20km for 25G DML lasers. Due to the carrier life time and the photon life time limitation, the DFB laser can only support 25Gb/s NRZ direct modulation but not support 40Gb/s NRZ direct modulation. Due to the high chirp of DML, the 25Gb/s DML with NRZ modulation can only operate in zero dispersion and O- band without serious dispersion penalty, but in O+ band, the dispersion penalty after 20km transmission is quite serious even for 25Gb/s DML laser.

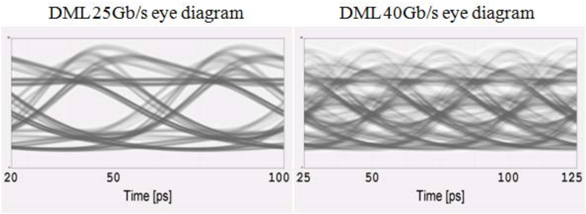

Figure 7.1-4 Simulated Eye diagram of DML laser with 25Gb/s and 40G NRZ modulation

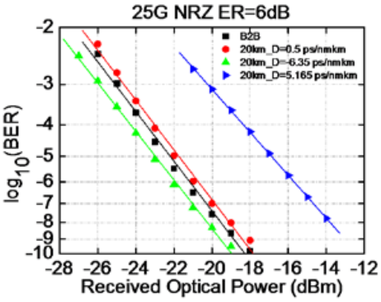

Figure 7.1-5 25Gb/s DML dispersion penalty comparison after 20km

We can extrapolate from 10 Gb/s the required NRZ receiver sensitivity for 25 Gb/s and 40 Gb/s, and the corresponding OLT minimum launch powers. For APD receivers, using the mode in [2][3], SNR(Signal noise ratio) of APD:

$$SNR = \frac{(MRP_{in})^2}{2qFM^2(MRP_{in} + I_d)\Delta f + 4k_B T\Delta f / R_L} \qquad (7.1\text{-}2)$$

Where:

P_{in} is the average receiver optical power

Δ f = receiver bandwidth

M = multiplication factor

F = excess noise factor

R = response of APD

Assume APD is photocurrent shot noise limited, then if increase the bandwidth Δ f by 2.5 times (for 25Gb/s NRZ), P_{in} must be at least increased by 2.5 times (4dB) to main the same SNR; similarly , if increase the bandwidth Δ f by 4 times (for ~~25Gb~~40Gb/s NRZ), P_{in} must be at least increased by 4 times (6 dB) to main the same SNR; while when bit rate increases, the M, R, F can’t be obtained same as 10Gb/s, so the sensitivity of APD will go~~es~~ even higher level(less sensitive) when bit rate goes to 40Gb/s. Accordingly the approximate~~ly~~ formula in [3] $P_{in} \propto B^{7/6}$, the sensitivity of 40Gb/s APD will be at least 7dB lower(less sensitive) than 10Gb/s APD.

We can take the parameters of XG-PON downstream in G.987.2 as a base line and extrapolate the ONU sensitivity and OLT transmitter launch power requirement for higher bit rates, which is shown in Table 7.1-2

Table 7.1-2 ~~.~~NRZ power requirements, downstream.

NRZ bit rate	**Rx sensitivity, downstream**	**Required transmit power min, N1 class**
10 Gb/s	-28 dBm	2 dBm
25 Gb/s	-24 dBm	6 dBm
40 Gb/s	-21 dBm	9 dBm
Note: assume OPP maintains same with XG-PON , which is highly wavelength dependent		

7.1.1.2 NRZ modulation assisted with DSP technology

DSP technology can be used to improve the performance of NRZ transmission via the compensation of inter-symbol interference (ISI), which may be caused by fiber chromatic dispersion and/or bandwidth limitation of the transmitter and the receiver. At 25 Gb/s, DSP-assisted NRZ is capable of transmission over 20 km in the C-band, while the conventional NRZ is not. On the other hand, if the O-band is chosen for 25-Gb/s per-wavelength transmission, fiber chromatic dispersion is no longer a concern that requires the use of DSP assistance. DSP-assistance has also been shown to allow the use of 10G-class optics for 25-Gb/s transmission, thereby lowering the cost of the optics. It remains to be seen if the lowered cost in optics can justify the additional cost associated with the use of DSP, i.e., the cost of the digital signal processor, the analog-to-digital converter (ADC), and/or the digital-to-analog converter (DAC).

The different frequency component of optical signal which has a certain spectral width in optical transmission system has different transmission rate~~,~~. ~~w~~When data rate goes beyond 10Gb/s, it will lead the signal to be broadened and result in serious inter symbol interference (ISI). If the effective bandwidth of the signal is greater than the effective bandwidth of the system, for example, utilizing existing 10G optics to transmit 25Gb/s signal , when the signal is transmitted through the system, it will lose a lot of important components ~~to~~ and will be distorted. In such case, optical fibre system can no longer be considered an infinite bandwidth communication channel. In order to overcome the above effects in high-speed optical system, equalization compensation is essential.

DSP-based equalizer system is to compensate for transmission-channel impairments such as frequency-dependent phase and amplitude distortion. Reasonable clock recovery and equalizer~~s~~ designs, such as feed-forward equalization (FFE), decision feedback equalization (DFE), maximum likelihood sequence equalization (MLSE) etc, make it easily recover the original signals ~~form~~ from distorted signals. According to the different requirements and application scenarios, equalizations with different structures and complexity are ~~born~~proposed.

Figure 7.1-6 shows an example of 28Gb/s NRZ modulation scheme in C-band based on DSP equalization. At the transmitter~~TX~~ side, a normal NRZ signal is transmitted by digital to analog ~~convertor~~ converter (DAC), then through a band limited optical link, the original NRZ signal is ~~degradation~~degraded. ~~So a~~At the ~~RX~~ receiver side, an equalization algorithm based on DSP ~~which~~ to compensate~~s~~ the bandwidth limitation and optical dispersion is used to recover the original signal.

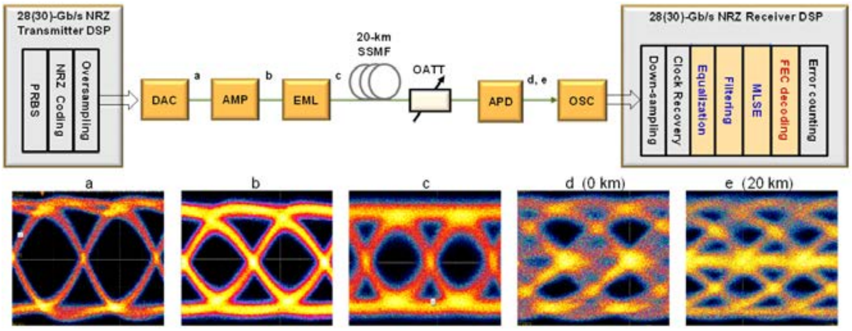

Figure 7.1-6. Schematic of the 28-Gb/s NRZ-DSP equalization experiment setup. (a-e): measured eye diagrams at different locations in the transmission link.

At the transmitter, PRBS is encoded into NRZ format and 2 times oversampled, before being converted to an analog RF signal by a high-speed digital-to-analog converter (DAC) with 56 GSa/s. An analog amplifier is used to adjust the RF signal to an appropriate level. A 10Gb/s EML with a center wavelength of ~1550 nm is used to convert the electrical signal to an optical signal. ~~.~~After 20km fiber transmission at the receiver side, 10Gb/s APD is used to directly detect the optical signal and followed by an ADC device to convert the signal to electrical digital signal. ~~..~~In the DSP function block, down-sampling and clock recovery are first performed. Equalization is then applied to compensate for the bandwidth-limitation induced inter-symbol interference (ISI). Finally, the FEC decoder processes the output from the equalization module and corrects the pre-FEC bit errors.

Another potential benefit of DSP-assisted NRZ is its capability to reliably recover the signal even at high received bit error ratio (BER), e.g., higher than 10^{-3}. This may allow advanced forward error correction (FEC) to be used to increase the link budget for 25-Gb/s NRZ transmission. In addition, the use of DSP may ease the implementation of multi-rate burst-mode clock data recovery (CDR), which could be needed for TDM coexistence between 25 Gb/s and 10 Gb/s upstream signals.

In summary, DSP-assisted NRZ offers several potential benefits, and its adoption in future PON systems depends on factors such as its associated cost, power consumption and commercial product availability. If DSP is to be adopted, it is likely to be first used in OLTs as~~ its~~ the OLT cost can ~~then~~ be shared among many ~~more~~ ONUs.

7.1.2 Electronic duo binary

EDB is one of the associated coding techniques~~,~~. As compared to NRZ, it is a three electrical level ~~of~~ and higher-order modulation format~~s~~.

[Editor note: update based on 170328_D5]

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~~As shown i~~In Figure 7.1-7, the left graph shows the NRZ waveform, the middle graph shows the EDB waveform at the same transmission rate~~s~~, and the right graph shows the corresponding power spectrum diagram. It is obviously that ~~, except for the difference between the two level and three level,~~ the frequency spectrum of EDB is half ~~that~~ of NRZ except the difference between the two level and three level. This will greatly improve the dispersion tolerance ability. EDB can be applied either at the transmitter and receiver, or just at the receiver. In both cases, it will improve the dispersion tolerance in the system and reduce the receiver bandwidth requirements.

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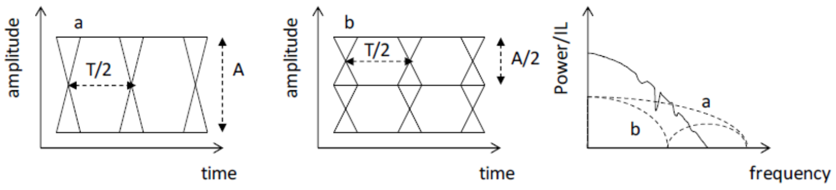

Figure 7.1-7. Schematic of NRZ waveform (left), EDB waveform(middle) and the corresponding power spectrum diagram(right).

Electronic duobinary data can be generated by sending NRZ On-Off Keying (NRZ-OOK) data through an electrical “delay-and-add” filter, creating a 3-level signal [4]. This filter has a z-transform of $1+z^{-1}$, which can be approximated by a low-pass filter (LPF) in the electrical domain. Duobinary coding is a correlative coding method, so to avoid error propagation, pre-coding of the data at the transmitter is needed [5].

~~The f~~Figure 7.1-8 shows the coding and decoding schematic diagram of EDB. In a typical EDB system, there are three parts: Pre-coder (differential encoding), en-coder and de-coder. The ~~P~~pre-coder part mainly completes the input stream differential coding, and the logic is implemented using XOR logic with feedback delay. The ~~E~~encoder part mainly completes coding related functions (the three level output~~),~~) by logically using the way of 1 bit time delay and add. At the receiver, a~~n~~ simple example of ~~simple~~ EDB decoder is an electrical circuit that includes a splitter, ~~2~~ two comparators of upper level detection and lower level detection, and an XOR gate.

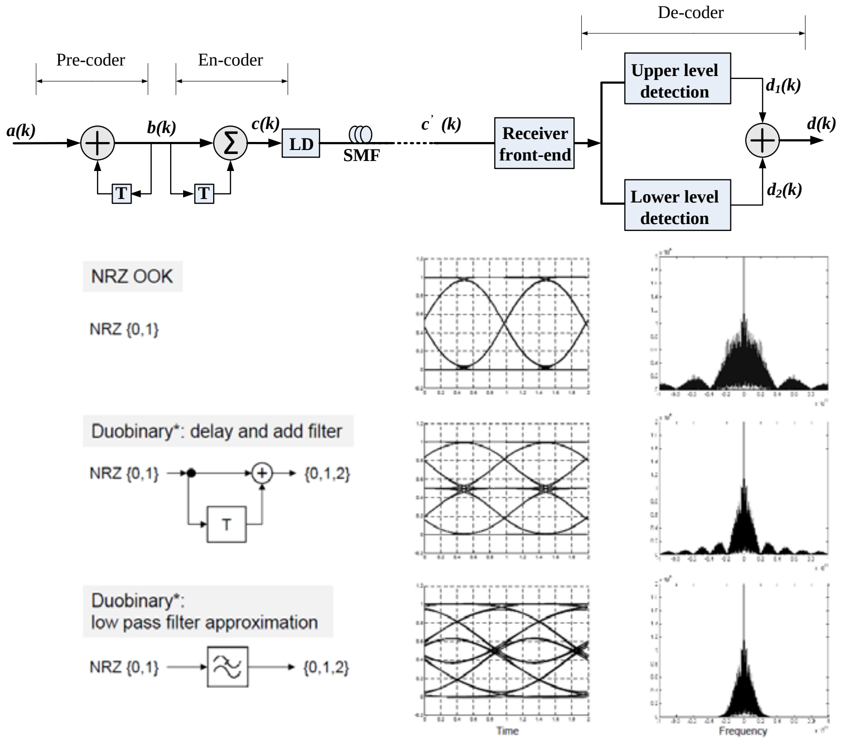

Figure 7.1-8. Coding and decoding schematic diagram of EDB

The duobinary LPF encoding can be realized by the bandwidth roll-off of either the transmitter or the receiver. The required bandwidths of the LPF are shown in Table 7.1-3.

Table 7.1-3: Duobinary LPF encoding bandwidths compared to NRZ

	10Gb/s	25Gb/s	40Gb/s
NRZ	7.5GHz	18.75GHz	30GHz
Electronic Duobinary	not in scope	7GHz	11GHz

~~From table 7.1-3,~~ As compared to NRZ, the payoff for EDB is~~, compared to NRZ,~~ a reduction in signal spectrum- and an increase in CD tolerance by approximately a factor of 2. These characteristics of duobinary mitigate the need for higher speed components and increase~~d~~ dispersion tolerance. ~~while~~ While the cost is higher decoding complexity~~,~~ and lower sensitivity (due to the three level eyediagram~~),~~). ~~s~~So optical amplifier (SOA) may be required by EDB to meet the same power budget of NRZ.

7.1.3 Optical duo binary

For NRZ system, dispersion has the most influence on the “1,0,1” ~~interval~~ sequence~~ for NRZ transmission system~~. Optical pulse phase of NRZ signal modulated by EAM or MZM has the same symbol. ~~Thus w~~When the pulse is broadened by the dispersion, “0” between the “1,0,1” sequence will have a certain optical intensity because of the two “1” pulse edge overlay. Pulse broadening increases with the transmission ~~increas~~distance increases~~ing of transmission distance~~, the optical intensity of “0” increase~~s~~d, eye opening is reduced because of ISI. Finally the performance of the receiver is heavily decreased~~ seriously~~.

Optical duo binary (ODB) has three levels “1,0,-1”. Although the two adjacent optical pulses ~~which have opposite symbols~~ have dispersion, pulse broadening will be offset ~~due to~~because they are the opposite symbols. Thus the ISI is reduced, dispersion tolerance is improved greatly. Dispersion characters of NRZ and ODB are shown ~~as~~ in ~~figure~~ Figure 7.1-9.

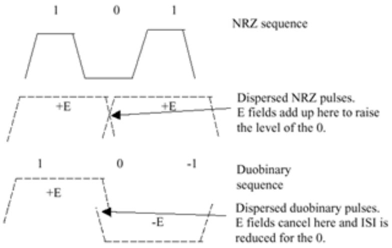

Figure 7.1-9. ODB interference offset to avoid ISI

~~Use phase character in the E/O transition. Amplitude of output optical signal is coincident. ODB signal can be received by normal NRZ receiver.~~

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There are three levels “1,0,-1” in DB electrical signal. “0” level should be biased on the NULL point (valley) of the MZM. Thus the optical intensity of level “1” and “-1” is coincident, but their phases are opposite. ODB ~~Use~~uses phase character in the E/O transition~~.~~, and the ~~A~~amplitude of output optical signal is coincident~~.~~, so ODB signal can be received by ~~normal~~regular NRZ receiver.

The ODB modulation principle is shown in ~~figure~~ Figure 7.1-10. The rectangular coordinate axes in the left bottom subfigure is the electrical signal voltage adding on the modulation RF port [7]. The solid line is the optical intensity modulation curve of MZM. The dash line is the phase modulation curve.

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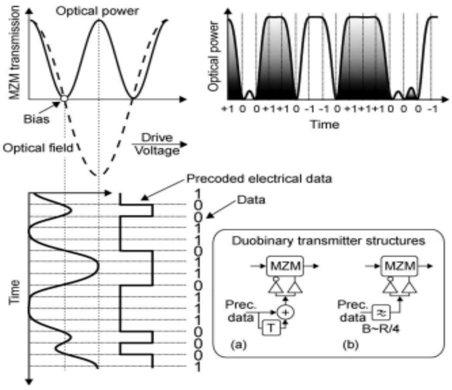

Figure 7.1-10 ODB modulation principle.

As an example, the figure 7.1-11 shows the coding and decoding schematic diagram of 25Gb/s ODB in C-band. The pre-coder and encoder schematic of ODB is same with EDB, the low pass filter first transforms the 25Gb/s NRZ signal to a ~~3~~ three-level~~s~~ duo binary signal. At the transmitter, a phase modulator, such as a 10Gb/s MZM at 1550nm operation wavelength, is used to transform the 3 levels electronic duo binary signal to an optical duo binary signal. This result is achieved with a MZM biased at its null point. With a ~~zero~~ “0” input, no light is transmitted, ~~but~~and the “+1” and “-1” inputs are transmitted as +E and –E electric fields, respectively. While this is a three-level signal in terms of the electric field, it is a two-level signal in terms of optical power. This scheme significantly reduces the complexity of the receiver (different with EDB), and ~~also~~ increases the chromatic dispersion tolerance. Because the “+1” and “-1” signal have the same amplitude in intensity, ~~T~~the decoder part of ODB ~~is the~~can conduct ~~operation of~~ modulo 2 operation~~, due to the “+1” and “-1” signal have the same amplitude in intensity~~, so the ODB detection is quite similar ~~with~~ to the NRZ detection.

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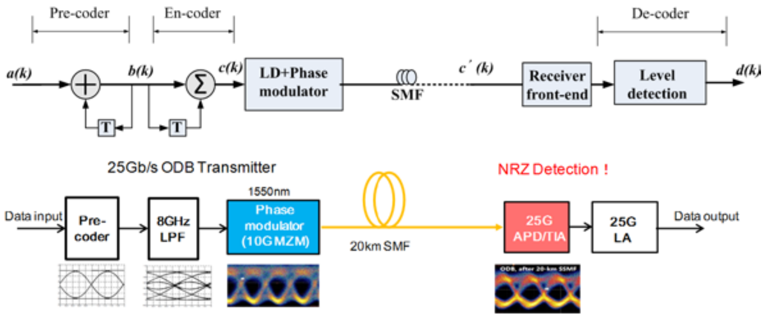

Figure 7.1-11. Coding and decoding schematic diagram of 25Gb/s ODB

7.1.4 PAM4 modulation

4 level pulse amplitude modulation (PAM4) is a form of signal modulation where the message information is encoded in the amplitude of 4 signal pulses. The principle of 25Gb/s PAM4 is shown in figure7.1-12. The baud rate of 25Gb/s PAM4 signal is only 12.5GBaud/s. The spectral efficiency is doubled. The dispersion tolerance of 25Gb/s PAM4 is 4 times of 25Gb/s NRZ. The transmitter of 25G PAM-4 modulation only needs a 12.5Gb/s EML and a 12.5Gb/s linear driver, and the receiver is a 12.5Gb/s linear APD ROSA. In order to re-use the existing industry chain, 10Gb/s optical devices can ~~even~~ be used for 25Gb/s PAM4 modulation instead of 12.5G optical components. ~~And then some~~ ~~e~~Electrical compensation algorithms can be adopted to compensate the bandwidth. PAM-4 coder and decoder chip is necessary for PAM4 modulation.

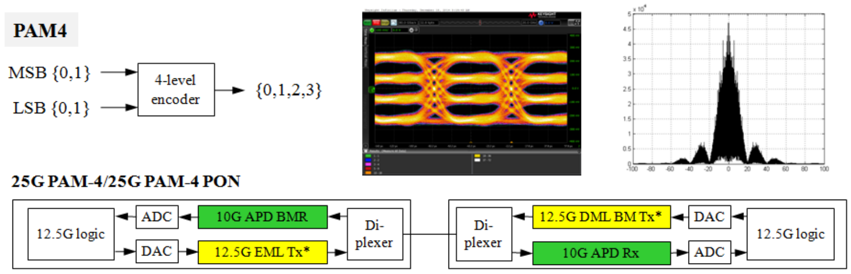

Figure 7.1-12. Schematic of PAM4 modulation

[Editors'notes: based on 170426_D53_ZTE_Modulation_Formats_for_G.sup.hsp]

7.1.5 DMT modulation

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While NRZ, duo-binary and PAM4 can be used for PON transmission above 10G per wavelength, Orthogonal Frequency Division Multiplexing modulation (OFDM) can also be utilized to achieve high data rate with low bandwidth optical transceivers. Moreover, deep integration with sophisticated electronic digital signal processing (DSP) introduces strong implementation flexibility and capabilities of compensating various transmission impairments.

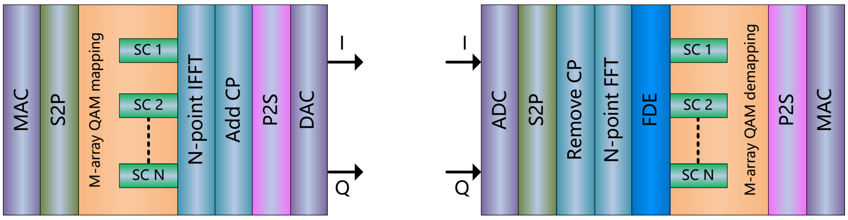

Figure 7.1-13 – Basic OFDM system architecture

The basic architecture of the electronic OFDM transmitter and receiver are shown in Figure 7.1-13. In the transmitter, high speed binary data is first parallelized (S/P), and then mapped to M-ary Quadrature Amplitude Modulation (QAM) symbols (e.g., M = 4, 8, 16…), and feed into a N-point inverse fast Fourier transform (IFFT) to generate a digital OFDM signal with N orthogonal subcarriers. After cyclic prefix (CP) insertion, the digital output is serialized and applied to a two-channel digital-to-analog converter (DAC). The output of in-phase (I) and quadrature (Q) components of the OFDM signal are then converted into fiber either by optical IQ modulator or direct optical intensity modulation. In the receiver, the I and Q signal components are digitized by a two-channel analog-to-digital converter (ADC), which is followed by serial-to-parallel conversion and cyclic prefix removal. An N-point fast Fourier transform (FFT) is used to digitally de-multiplex the N OFDM subcarriers. Single-tap frequency domain equalization (FDE) maybe performed to correct linear impairments (e.g., chromatic dispersion) on each of the N subcarriers, which is followed by M-ary QAM symbol de-mapping. Finally, the received bits are serialized to recover the transmitted data.

One of the major merits of using OFDM is that frequency domain multiplexing can be introduced into PON network. In current PON system, the whole PON capacity can be shared among users via both wavelength domain (i.e., WDM) and time domain (i.e., TDM). While in OFDM systems, extra frequency domain can be accessed by means of IFFT/FFT via DSP. One (or more) subcarrier(s) can be assigned either dynamically or statically from the entire OFDM band to different users, as shown in Figure 7.1-14. In addition, frequency domain multiplexing can also work together with wavelength and time domains multiplexing to achieve flexible bandwidth sharing with multiple granularities.

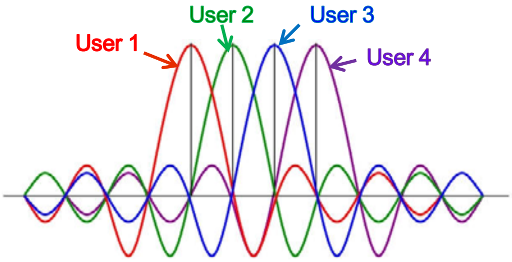

Figure 7.1-14 – Frequency-domain OFDM subcarrier multiplexing for multi-user access

For 10G above per wavelength PON systems, OFDM is expected to generate high-speed signals by low bandwidth transceivers, for example, 25G or 40G data rate can be supported by using 10G directly modulated DFB lasers (DMLs) or external modulated lasers (EMLs), and 10G APD/PIN detectors. In order to avoid complex optical I/Q modulator, conjugate symmetry can be exploited for simple implementation by using single-channel DAC/ADC instead of analog I/Q modulator/demodulators, as known as Discrete Multi-tone (DMT). Figure 7.1-15 shows the example architecture with DMT modulation.

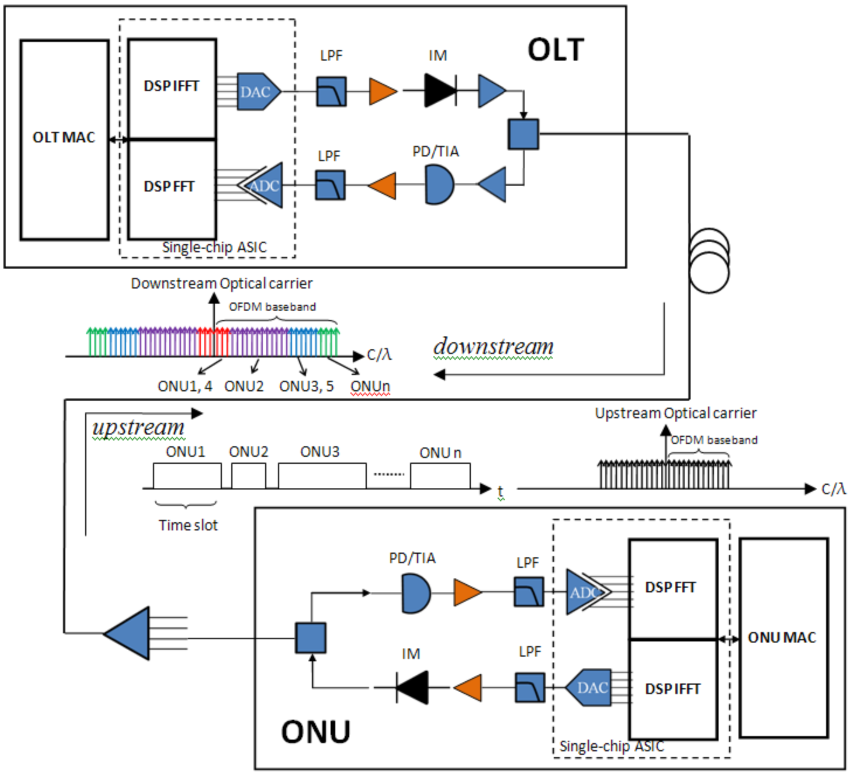

Figure 7.1-15 –example architecture of DMT modulation

At the OLT transmit in the downstream direction, digital baseband signal is generated by DMT modulator based on a DSP with QAM mapping and IFFT, then, it is converted to analog signal using a single channel DAC. An Intensity Modulator (IM) is used to convert the baseband signal to optical intensity for downstream transmission. At the ONU reception, the downstream signal is directly detected by a linear optical PIN or APD receiver, and then sampled by ADC. Then FFT and QAM de-mapping are processed by DSP, so the downstream data is re-generated. Downstream multiplexing can be conducted with different granularities. A group of ONUs may be assigned by one or more sub-carriers in frequency domain. The available bandwidth of each sub-carrier or sub-carrier group can be further divided among ONUs in time domain.

As shown in Figure 7.1-15, time domain multiple access (TDMA) with DMT modulation can be used in the upstream direction. At the ONU transmit side, a DMT digital baseband signal is generated by DSP, and then converted into optical intensity using DAC and IM modulator and transmitted in dedicated time slot assigned to each ONU by OLT. At the OLT receive side, the upstream signal in each time slot is directly detected by a burst mode receiver and digitized by ADC, and then DSP fulfils the burst clock recovery and completes the DMT demodulation. Frequency domain multiple access (FDMA) can also be supported in upstream, but necessitates more accurate frequency control mechanisms.

[Editors'note based on 170426_D54_NTT_G.sup.HSP_Receiver_Techs in Kobe]

7.1.6 Modulation technologies comparison

[Editors'note: living list item 11, based on 170725_D3]

Generally speaking, different modulation technologies have different advantages and disadvantages, different modulation technologies can meet different requirements in different scenarios. The coexistence requirement, line rate and power budget requirement will have big impact on modulation technology selection. Considering the following reasons: 1) the main high bandwidth optic industry chain above 10G are in O-band , 2) re-using the existing ODN is the general basic requirement, 3) 25Gb/s and 50Gb/s are the main feasible line rates per wavelength in this stage. In this section, we compare the advantages and disadvantages at 25Gb/s and 50Gb/s line rates in O-band and assume achieving at least 29dB power budget is a basic requirements.

1). Overall comparison

Attributes	**NRZ**	**EDB**		**ODB**	**PAM-4**	**OFDM**
		@ Tx&Rx	**@Rx Only**			
Required optical component bandwidth at Tx	~0.9 B0 (B0 is the bit rate)	~1/3 B0 (B0 is the bit rate)	~0.9 B0 (B0 is the bit rate)	~1/3 B0 (B0 is the bit rate)	>0.45 B0 (B0 is the bit rate)	<<B0
Required optical component bandwidth at Rx	0.75 B0	~3/8 B0	~1/3 B0	0.75 B0 (B0 is the bit rate)	>3/8 B0	<<B0
Approx. back-to-back Rx sensitivity penalty compared to NRZ (dB)	0	~2	~1-2	~1	~3.0	>4
Dispersion tolerance	+	++	++	+++	+++	++++
Transmitter linearity required	no	no	no	no	yes	YES (high linearity requirement)

Receiver linearity required	no	quasi-linearity needed	quasi-linearity needed	no	yes	YES (high linearity requirement)
Complexity At transmitter	+	+	+	+++ phase modulator needed, MZM	++	++++++++ (DSP needed at Tx)
Electronics complexity At receiver	+	++ (EDB decoder)	++ (EDB decoder)	+ (detection same as NRZ)	++++ (PAM4 encoder and decoder)	++++++++ (DSP needed at Rx)

Generally speaking, NRZ has the best simplicity and highest receiver sensitivity, but it also requires the highest bandwidth on optics and has the lowest dispersion tolerance. Duo binary and PAM4 can decrease the bandwidth requirement of optics and better dispersion tolerance but with the cost of lower receiver sensitivity and higher electronics complexity. OFDM has the lowest bandwidth requirement on optics, but it requires high linearity on optics, complicated electronic process and loses lot of receiver sensitivity. Between EDB and ODB, generally speaking, ODB needs a more complicated modulator in the transmitter side but simplifies the receiver (similar to NRZ receiver).

2) Comparison at 25Gb/s

Attributes at 25Gb/s	NRZ	EDB		ODB	PAM-4	OFDM/DMT
		@ Tx&Rx	@ Rx only			
OLT Transmitter	25G EML/DML	10G EML	25G EML/DML	10G MZM	12.5G EML	10G linear DFB + DSP needed
Receiver	25G APD	12.5G APD	10G APD	25G APD	12.5G APD	10G linear APD
ONU Electronics	25G TIA ,LDD	quasi-linear 12.5G TIA; EDB decoder	quasi-linear 10G TIA; EDB decoder	25G TIA	PAM4 Decoder	25G DSP
Dispersion sustainability	Medium/Good	Good	Good	Good	Good	Very Good
Challenges to meet 29dB power budget	Low	Low/Medium	Low/Medium	Low/Medium	medium	high

Commented [l4]: This row has been updated from "dispersion penalty" to "Dispersion sustainability" after the meeting based on the comments on the meeting.

For 25Gb/s in O-band, due to the low fiber dispersion coefficient there and wide availability of 25Gb/s optics, the NRZ modulation without dispersion compensation seems the best solution due to its simplicity and high receiver sensitivity.

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3) Comparison at 50Gb/s

Attributes at 50Gb/s	**NRZ**	**EDB**		**ODB**	**PAM-4**	**OFDM/DMT**
		@ Tx&Rx	**@Rx Only**			
OLT Transmitter	50G EML	25G EML	50G EML/DML	20G MZM	25G EML	10G linear DFB + DSP needed
Receiver	50G APD	25G APD	25G APD	50G APD	25G APD	10G linear APD
ONU Electronics	50G TIA ,LDD	quasi-linear 25G TIA; EDB decoder	quasi-linear 25G TIA; EDB decoder	50G TIA	25G PAM4 Decoder	50G DSP
Dispersion Sustainability	Poor	Medium	Medium	Medium	Medium	Good
Challenges to meet 29dB power budget	Medium	Medium/High	Medium/High	Medium/High	High	Very high!!!

Commented [l6]: This row has been updated after the meeting based on the comments on the meeting.

At 50Gb/s line rate, the high bandwidth requirement on optics for NRZ will become a big issue. In current industry chain, only very few 40Gb/s or 50Gb/s commercial EML TOSA or MZM TOSA are available with very high cost. There aren't any commercial 50Gb/s APD products in the market by far. So advanced modulation technologies, such as PAM4 or EDB, seem more practical solutions for 50Gb/s line rate per wavelength. Of course, the challenge for 50Gb/s is how to meet the at least 29dB power budget requirement. Take the 25Gbaud/s PAM4 as example, the sensitivity of 25Gbaud/s PAM4 is at least 4.8dB worse than 25Gb/s NRZ due to the eye openness of PAM4 is only 1/3 of that in NRZ, how to migrate this sensitivity gap and achieve same power budget with 25Gb/s is the key issue for 50Gb/s per wavelength.

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7.2 Transmitter and receiver technologies

We assume to realize the followings for the discussion of the receiver technologies.

- Higher bitrate (25G to 40Gbit/s) with keeping standard optical budgets (N1, N2, E1, E2).
- Per-lambda upgrade of NG-PON2, i.e. TDM/TDMA-based shared access.

Figure 7.2-1 illustrates the system configuration we assume. Because the ONU receiver is likely to be based on Direct Detection (DD), we focus on the OLT receiver to receive the upstream burst mode PON signals.

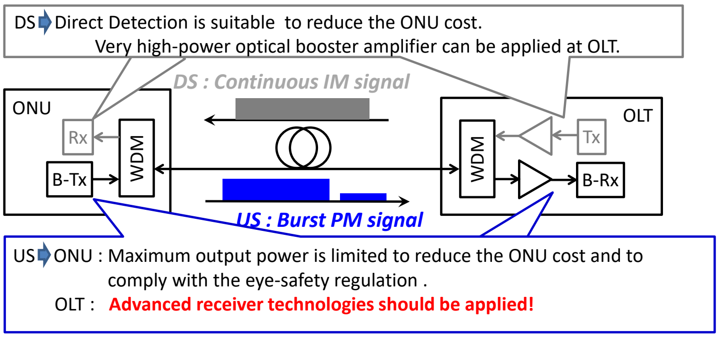
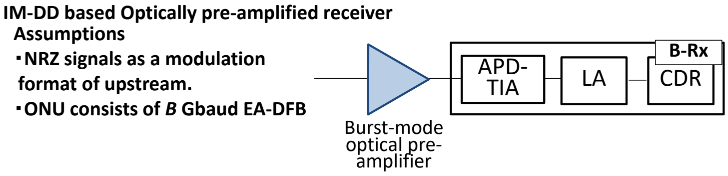
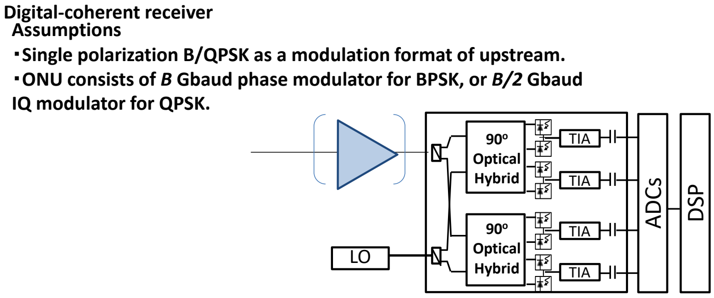


Figure 7.2-1 – System configuration assumed in this study.

Figure 7.2-2 illustrates schematics of two receiver technologies we discuss; one is the Intensity Modulation (IM) - DD based optically pre-amplified receiver and the other is the digital-coherent receiver. For the IM-DD based optically pre-amplified receiver, Non Return to Zero (NRZ) signals are assumed as a modulation format. We assume that the ONU transmitter consists of B Gbaud EA-DFB transmitter. For the digital-coherent receiver, single polarization BPSK and QPSK are assumed as a modulation format. ONU consists of B Gbaud phase modulator for BPSK, or B/2 Gbaud IQ modulator for QPSK.



(a)

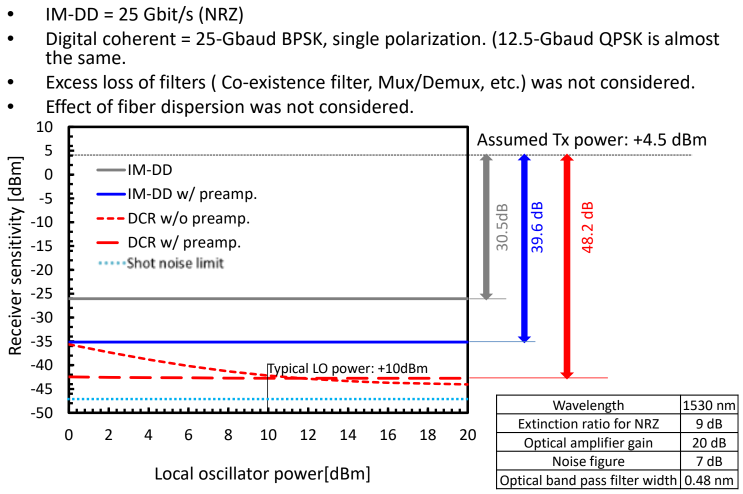


(b)

Figure 7.2-2 – Receiver technologies.

Calculation and observation

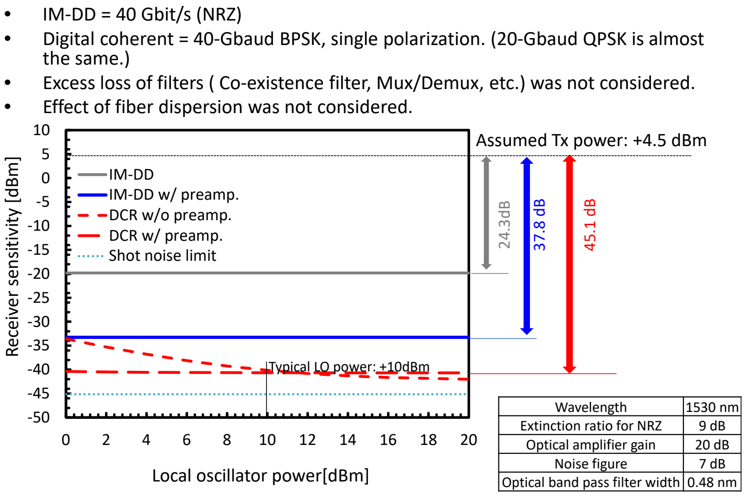
Figures 7.2-3 (a) and (b) show achievable power budget calculated for the cases of 25 Gbit/s and 40 Gbit/s, respectively. Excess loss of filters (Co-existence filter, Mux/Demux, etc.) was not considered. Effect of fiber dispersion was not considered, either.



- IM-DD = 25 Gbit/s (NRZ)
- Digital coherent = 25-Gbaud BPSK, single polarization. (12.5-Gbaud QPSK is almost the same.
- Excess loss of filters (Co-existence filter, Mux/Demux, etc.) was not considered.
- Effect of fiber dispersion was not considered.

Wavelength	1530 nm
Extinction ratio for NRZ	9 dB
Optical amplifier gain	20 dB
Noise figure	7 dB
Optical band pass filter width	0.48 nm

(a)



- IM-DD = 40 Gbit/s (NRZ)
- Digital coherent = 40-Gbaud BPSK, single polarization. (20-Gbaud QPSK is almost the same.)
- Excess loss of filters (Co-existence filter, Mux/Demux, etc.) was not considered.
- Effect of fiber dispersion was not considered.

Wavelength	1530 nm
Extinction ratio for NRZ	9 dB
Optical amplifier gain	20 dB
Noise figure	7 dB
Optical band pass filter width	0.48 nm

(b)

Figure 7.2-3 – Achievable power budget.

For the IM-DD based optically pre-amplified receiver, we observe the followings:

- E2 class (maximum budget: 35dB) can be barely supported at both 25G and 40Gbit/s.
- Considering the optical path penalties (optical dispersion, raman depletion, etc.) and excess losses of optical components (Mux/Demux, coupling loss, etc.), it might not meet the requirements.
- Optical/electrical chromatic dispersion compensations are mandatory.

For the digital-coherent receiver, we observe the followings:

- E2 class can be supported with a sufficient margin even for 40 Gbit/s.
- Chromatic dispersion is compensated by the aid of Digital signal processing, without any compensations in the optical domain (such as chirp-managed laser, dispersion shift fiber, etc.).

It is expected to further expand the reach (i.e. >>40km) and the speed (i.e. >>40Gbit/s/wavelength).

[Editors'notes: based on 170426_D55_HW_Optical amplifiers for above 10G]

7.3 Optical Amplifier technologies

When bit rate goes to above 10Gb/s, generally speaking, the sensitivity of the receiver goes to a higher number (less sensitive) compared with 10Gb/s, due to 1) higher band width and consequently more noise power and 2) smaller chip area which will result in lower responsivity. On the other hand, the chip area of transmitter also needs to go even smaller to achieve higher bandwidth, it will be more challenging to achieve the same launch power for the transmitter. In multiple wavelength system architecture, the extra insertion loss of mux/demux is also need to be overcome. In order to achieve the same power budget and reuse the legacy ODN, optical amplifiers may be need in systems based on 10Gb/s above line rates. This chapter shows the optical amplifier technologies which can be used for 10Gb/s above systems.

7.3.1 Erbium-doped Optical Fiber Amplifier (EDFA)

The erbium-doped fiber amplifier (EDFA) is optical amplifier that use an Erbium doped optical fiber as a gain medium to amplify an optical signal. The signal to be amplified and a pump laser are multiplexed into the Erbium doped fiber, and the signal is amplified through interaction with the doping Erbium ions. EDFA is the most deployed fiber amplifier as its amplification window coincides with the third transmission window of silica-based optical fiber. It has the advantage of high gain, low noise figure and low polarization dependence. It is very widely used in DWDM fiber transmission system.

Currently, two bands EDFA have been developed in the third transmission window commercially–C-band (from approximately 1525 nm–1565 nm) and the L-band (from approximately 1570 nm to 1610 nm). If the wavelengths are defined in C-band or L-band, EDFA will be a good option to provide high gain and help to meet the required power budget. It can be used both in transmitter side as boost amplifier and receiver side as pre-amplifier.

The disadvantage of EDFA amplifier is its high footprint and high cost. Generally speaking, it’s more economic to be used in a multiple wavelengths system, which the multiple channels can share the same amplifier and cost.

If the wavelengths are in S-band (1490nm region) or O-band (1300nm region), it needs thulium or praseodymium doped fiber amplifiers, but such doped fiber amplifiers haven’t been developed in any commercial system by far.

7.3.2 Semiconductor optical amplifier

Semiconductor optical amplifiers (SOAs) are amplifiers which use a semiconductor to provide the gain medium. Compared with EDFA, SOA can only provide medium gain and has higher noise figure, but SOA is of small size, electrically pumped and much less expensive than EDFA. SOA can also be integrated with semiconductor lasers, modulators, detectors, etc. SOA is available in every semiconductor laser operating wavelength band, such as in O-band, S-band ,C-band, L-band, etc.

In the transmitter side, the SOA can be used to boost the launch power. The most straight forward way is integrating an SOA with the transmitter chip. Figure 7.3-1 shows the schematic of a 10Gb/s EML transmitter integrated with an SOA on the laser chip. The middle figure of 7.3-1 shows the DFB+EML packaged BOSA integrated with an SOA inside. Such BOSA can be assembled in a XFP module. The launch power with SOA integrated can be 8~10dBm. If we want to enhance the power budget of the downstream, integrating an SOA in the OLT transmitter will be the most suitable way, due to it only increases a small cost in the OLT transmitter side, is able to maintain same OLT ports density, doesn’t need extra space in OLT and still keeps the ONU with low challenge and low cost.

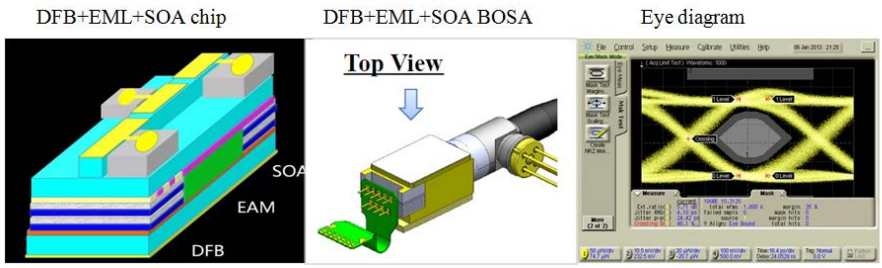


Figure 7.3-1 Schematic of EML transmitter with SOA integrated on the laser chip

The SOA can also be used in the receiver side as pre-amplifier. Due to the relative high noise figure of SOA, a lot of ASE noise will be introduced after the signal passes through the SOA pre-amplifier. A narrow pass band filter can be used to improve the signal noise ratio distinctly after the SOA. Figure 7.3-2 shows the spectrums when different narrow band pass filters are applied after the SOA pre-amplifier. From the figure 7.3-2, the narrow band filter can eliminate the ASE noise into the detector by a big extent, consequently can enhance the sensitivity of the receiver. Of course, there will be some tradeoff between the channel width and the gain performance of the pre-amplifier.

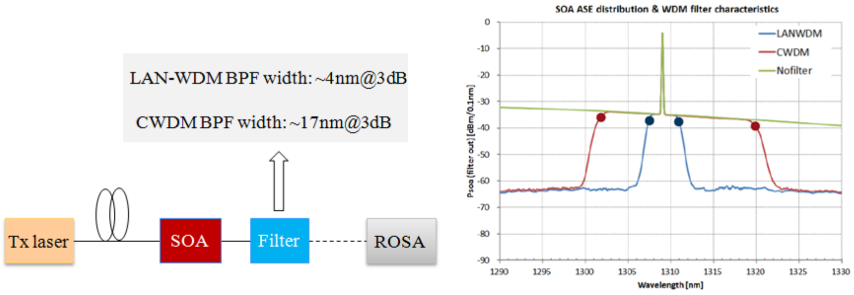
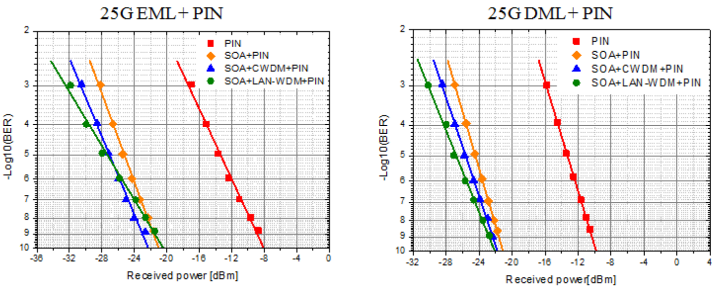


Figure 7.3-2 SOA spectrum after narrow band pass filters

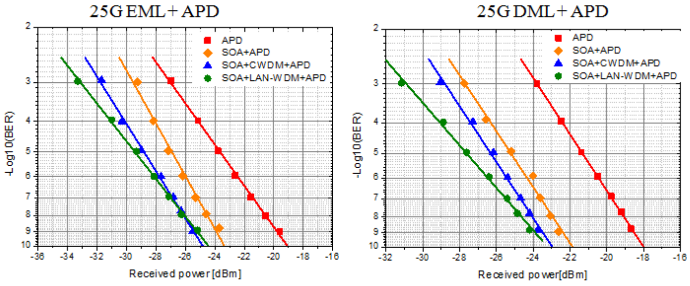
Generally speaking, there can be two configurations- SOA+PIN and SOA+APD. Figure 7.3-3 shows some experiment results on the performance of SOA+25Gb/s PIN receiver. The experiment setup is as left figure in Figure 7.3-2, a 25Gb/s EML or a 25Gb/s DML with NRZ modulation is used as the transmitter, the 25Gb/s signal through an variable optical attenuator goes in to the SOA preamplifier. A CWDM band pass filter (with ~17nm 3dB pass band width) and a LAN-WDM band pass filter (with ~4nm 3dB pass band width) are applied before the 25G PIN receiver. The small signal gain of the SOA at 25℃ is round about 20dB, noise figure is round 8dB. The extinction ratio of 25G EML is ~10dB, and the extinction of 25G DML is ~5.6dB. From the figure 7.3-3, the SOA can provide more than 14dB sensitive gain for the 25Gb/s EML signal and 25Gb/s DML, if a narrow LAN WDM-filter is applied before the PIN detector.



	25G PIN+SOA Receiver sensitivity @BER=1E-3			
	25G PIN	PIN+SOA No filter	PIN+SOA With CWDM filter	PIN+SOA with LAN-WDM filter
EML transmitter	-17 dBm	-28.2 dBm	-30.4 dBm	-31.8 dBm
DML transmitter	-15.8 dBm	-27.0 dBm	-28.5 dBm	-30.2 dBm

Figure 7.3-3 25Gb/s PIN+SOA receiver performance on EML and DML singal

Figure 7.3-4 shows the experiment results on the performance of SOA+25Gb/s APD receiver with the same condition in 7.3-3. From the figure for 25G APD receiver, the SOA can provide another round 6~7dB sensitivity gain for EML and DML signal when a narrow LAN-WDM filter is applied between the APD and SOA.



	25G APD+SOA Receiver sensitivity @BER=1E-3			
	25G APD	APD+SOA No filter	APD+SOA With CWDM filter	APD+SOA with LAN-WDM filter
EML transmitter	-27 dBm	-29.2 dBm	-31.6 dBm	-33.1 dBm
DML transmitter	-23.8 dBm	-27.7 dBm	-29.0 dBm	-31.0 dBm

Figure 7.3-4 25Gb/s APD+SOA receiver performance on EML and DML singal

Based on the comparison of Figure 7.3-3 and 7.3-4, SOA+APD can only provide extra ~1dB gain compared with SOA+PIN. If the sensitivity is not that insufficient, the PIN+SOA receiver will have the advantage of smaller footprint and lower cost, compared with APD+SOA.

8 TBD