Number of Wavelengths vs. Data Bit-Rate per Wavelength in Modern Optical Networks

BROADBAND COMMUNICATIONS PRODUCTS

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Abstract

In this paper, projections for increased bandwidth requirements in Metro core/Metro access networks, driven primarily by Video-on-Demand (VOD) market, are first presented. These projections are based on VOD penetration rate, peak simultaneous usage (contention) rate and percentage of HDTV streams. Next, the economics for 2.5 Giga bits per second (Gbps), 10 Gbps and 40 Gbps solutions are presented, based on total number of Gbps of bandwidth needed.

Power budget requirements, and corresponding reduction of the dynamic range with bit rate per wavelength increase, along with dispersion and non-linear effect limitations are then presented.

Finally, practical implementations of 40 Gbps higher order modulation formats that operate on currently deployed infrastructure are discussed.

Typical Centralized System

A system design was carried out over an idealized typical MSO division shown in Figure 1. The Cable division supports between 350 to 380 thousand homes passed with a stable cable penetration at 65%. It is further assumed that typical MSO division-wide rings are approximately 320 km and are typically made up of 8 digital hubs. Detailed system characteristics are presented subsequently. The system simulation details cumulative transport equipment and infrastructure cost thru progressive time periods for each distinct transport speed (2.5 Gbps, 10 Gbps and 40 Gbps) option selected.

System design involves a determination of the following costs:

- INFRASTRUCTURE COST: Appropriate account of infrastructure, including EDFAs, Dispersion compensation modules, DWDM passives, but not the cost of additional fibers themselves.
- TRANSPORT COST: The cost on the transmit sites include the optical transmitters and equipment needed to produce route diversity. The cost on the receive sites include the needed transport receivers, but do not include the Edge device (MPEG multiplexing, QAM modulation and RF up-conversion unit). We assume here MPEG 2 transport with 4 Mb/s for SDTV and 20 Mb/s for HDTV streams.

Various techniques such as the industry's migration towards more complex compression schemes (MPEG 4 or equivalent) and the proliferation of Personal Video Recorders (PVRs) will contribute to a reduction in the transport bandwidth. While these techniques are not discussed in this paper, their benefit in relation to cost of implementation should be considered in addition to transport methodologies presented in this paper for a complete system analysis.

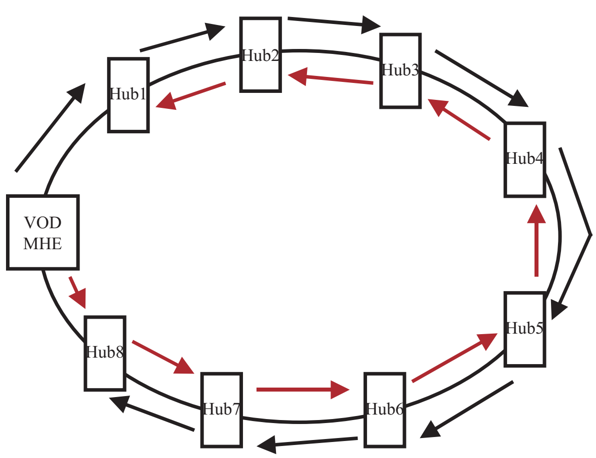


Figure 1. Typical Centralized System

System Characteristics

Time Period	Homes Passed	Cable Penetration	Digital Penetration	Peak Simultaneous Usage	HDTV on Demand Request Rate	STB/Digital Subcriber	Maximum Length (km)	Number of Active Hub Receiver Sites
1	350,000	65%	30%	3%	0%	1.4	320	8
2	353,500	65%	35%	9%	5%	1.5	325	8
3	357,035	65%	40%	14%	10%	1.6	330	8
4	360,605	65%	45%	20%	15%	1.6	335	8
5	364,211	65%	50%	25%	20%	1.7	340	8
6	367,854	65%	55%	31%	25%	1.8	345	8
7	371,532	65%	60%	36%	30%	1.9	350	8
8	375,247	65%	65%	42%	35%	1.9	355	8
9	379,000	65%	70%	47%	40%	2.0	360	8
10	382,790	65%	75%	53%	45%	2.1	365	8

The table presented above illustrates potential progressions for an idealized MSO division experiencing greater success with its VOD offerings over successive time periods (not necessarily years) characterized by VOD parameters described along side the time period.

- The digital penetration is progressively increased to 75% indicating the penetration of digital set top boxes
- The peak simultaneous usage (also referred to as contention) of the interactive capability (assumed inherent in the digital cable subscriber set-top-box) progressively increases from the commonly found 3% to 45% indicating the maximum digital cable subscribers at some regular point in a week engaged in an interactive television experience simultaneously
- The progressive growth in STBs per home is indicated in the next column

If these projections turn out to be correct, by way of example, for time period 4, the cumulative requested streams in the entire system would have been 360,605 HP*65% Cable Penetration*45% Digital Penetration*20% Peak simultaneous Usage*1.6 Average number of active STBs/Digital home yielding 33,753 streams. Of these 33,753 streams, 15% would have been HDTV streams accounting for roughly 100 Gbps and the remaining 85% would have been SDTV streams accounting for 115 Gbps, making the cumulative data rate the system would have handled at 215 Gbps.

Transport Cost

Figure 2 presents the results from the system simulation detailing cumulative transport equipment cost through progressive time periods for each distinct transport speed option selected. By way of observation, it is easily seen that the 2.5 Gbps transport option is the least expensive transport option with progressively higher speeds costing more. This is expected for two reasons.

- Generally speaking, the 2.5 Gbps transport option provides the highest granularity of the speeds presented providing for a maximum of 600 MPEG 2 SDTV streams with proper aggregation or of 480 streams of two fully loaded GbE channels without any aggregation thereby providing a granular way of dropping off needed data at receive sites
- In addition, the 2.5 Gbps optics are commercially more mature than their 10 Gbps or 40 Gbps counterparts.

Due to similar explanation, it is also observed that 10 Gbps transport costs are between those of 2.5 Gbps transport and of 40 Gbps transport. Transport costs are only one part of the equation, and before a decision is made of the transport speeds, appropriate infrastructure cost have to be considered and are the subject of the next section.

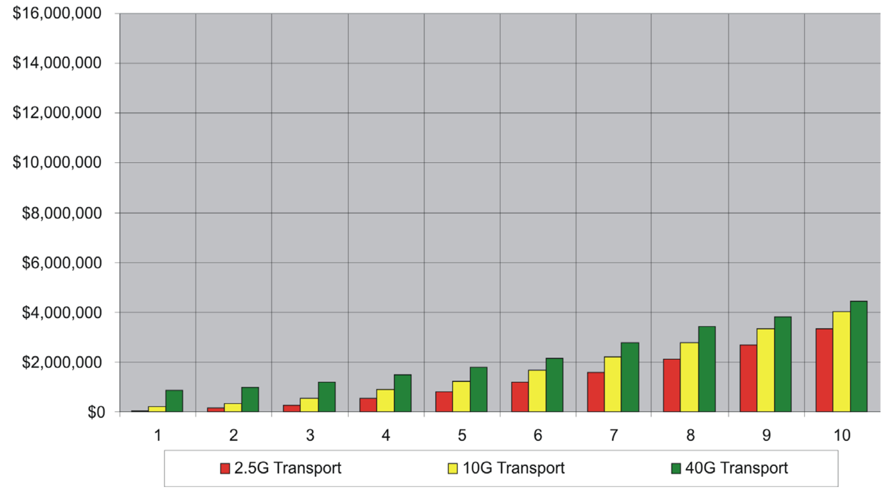


Figure 2. Transport Cost

Infrastructure Cost

Figure 3 shows the cost of infrastructure in relation to the transport speed. Infrastructure cost (defined earlier as EDFAs and optical passives) is a significant component of the overall cost of system design and has an inverse relation to the transport speed chosen. Infrastructure cost is proportional to the number of fibers that one would deploy for a system to function. Each new fiber requires an infrastructure charge to account for EDFAs, and other passives for the receive sites.

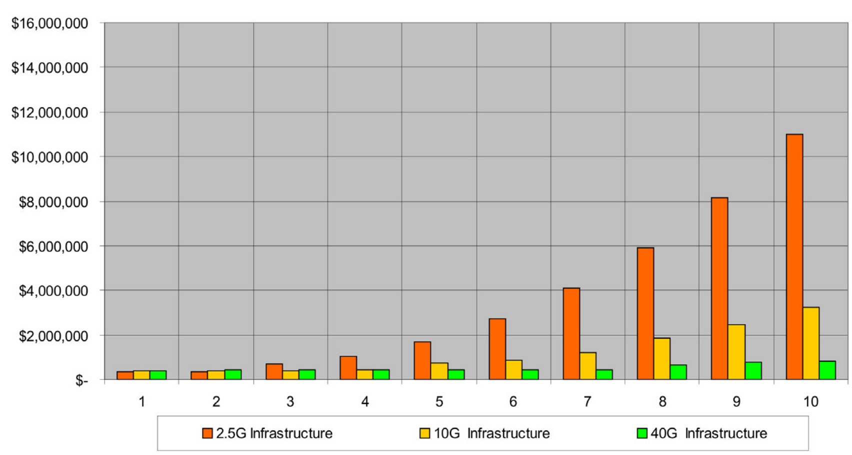


Figure 3. Infrastructure Cost

A depiction of the number of fibers needed for each transport option is shown in Figure 4. For example, it is seen that for the time period 8, a pure 2.5 Gbps transport option would require 16 fibers whereas the 10 Gbps solution would require 4 fibers and the 40 Gbps would have needed 1 fiber. This drastic reduction in fiber count provides for the substantial reduction in infrastructure cost for the entire system.

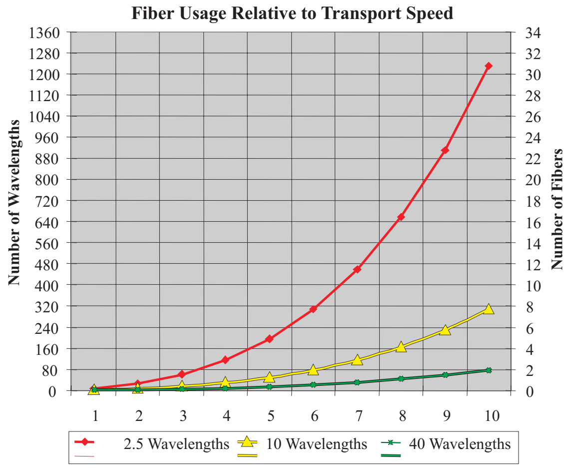


Figure 4. Fibers Required for Various Transport Speeds

Total System Cost

When the cumulative transport and infrastructure costs are combined, the relative strengths of each transport option become evident. As indicated in Figure 5, up to time period 3 the 2.5 Gbps option appears to be the least expensive, after this, the infrastructure cost of the 2.5 Gbps option increases at a substantial rate and tracks the fibers usage presented earlier. From time period 4 to 6, the 10 Gbps option seems to be the least expensive, beyond this point, the 10 Gbps cost rises in proportion to the fiber usage.

For high request rates (possible with increasing digital penetration and higher HDTV request rates), the 40 Gbps option is the least expensive since the available infrastructure is used most efficiently with following assumptions:

- a suitable higher order optical modulation scheme is chosen to implement the 40 Gbps transport system
- that the infrastructure costs of the 40 Gbps option is a small premium over the 10 Gbps option

Further optimization that simultaneously minimizes the initial cost while providing the best utilization of infrastructure would require simultaneously multiplexed 2.5 Gbps (NRZ), 10 Gbps (NRZ), and 40 Gbps (higher order modulation scheme) options at strategic time periods. The higher order 40 Gbps transport architecture along with its technical challenges are the next subjects of discussion.

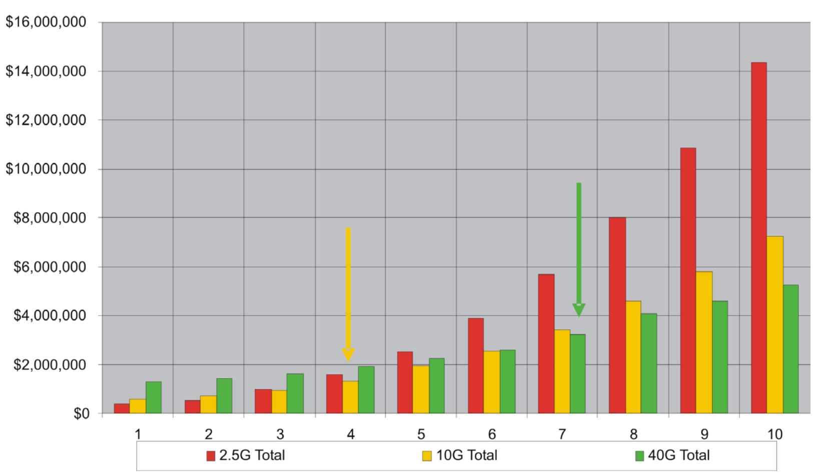


Figure 5. Total System Cost

Upgrading to 10 Gbps

Practical 10 Gbs systems yield point-to-point reaches of 80-120 km (and more with enhanced error correction). Using dispersion compensation, 600 km DWDM rings can be built with more than 100 km chromatic dispersion compensation operating windows. In many cases power budgets designed for 2.5 Gbps allow 80 km EDFA spacing such that an upgrade to 10 Gbs can largely re-use existing SMF fiber installations and use existing EDFA amplifier sites.

Polarization-mode Dispersion is small enough on most practical systems (except a limited percentage of legacy fiber) such that active PMD compensation is not required. A modest system cost impact results for a 10 Gbs DWDM system in comparison with a 2.5 Gbs DWDM system. Upgrades on an existing 2.5 Gbs system are also possible because the 10 Gbs modulation format does not exclude other modulation formats on adjacent wavelengths, provided power budgets and limits (to avoid non-linearities) are met.

Upgrading to 40 Gbps

Practical standard 40 Gbs systems (NRZ or RZ) yield point-to-point reaches of only about 4 km on SMF. Using adaptive chromatic dispersion compensation, DWDM rings could be built but in many cases lower dispersion fiber needs to be installed. Power budgets are reduced such that costly Raman amplifiers need to be applied to re-use existing optical amplifier sites. Polarization-mode Dispersion is critical in most practical systems (except newly installed low-PMD fiber types) such that active PMD compensation is generally required.

As a result, a very large system cost impact would result for a 40 Gbps standard modulation DWDM system in comparison with a 2.5 or even 10 Gbps DWDM system. Upgrades on an existing 2.5 Gbps system are possible because the 40 Gbps modulation (just like 10 Gbs modulation) does not exclude other modulation formats on adjacent wavelengths, however, provided power budgets and limits (to avoid non-linearities) that must be met are much more stringent.

Finally, the spectral width of an RZ 40 Gbps system is as much as 100 GHz (unless special techniques such as SSB and/or CS-RZ are used). As a consequence channel spacing of standard modulated 40 Gbps systems is at least twice that of practical 10 Gbps systems (50 GHz is practical) and the fiber capacity enhancement is limited.

NRZ Power Budget Requirements

Standard On-Off-Keying (OOK) Non Return-to-Zero (NRZ) modulation format, standard single mode (SSMF) fiber and multiple wavelengths on a wavelength division multiplexed (WDM) link are assumptions for the power budget requirements in Figure 6. Noise-limit lines (left-most "waterfall" lines) for 2.5 and 10 Gbps are based on Avalanche Photo Diode (APD) receiver; noise limit lines for 40 Gbps are based on a PIN diode receiver with an integrated semiconductor optical amplifier (SOA). No dispersion penalty is taken into account for any of these three cases. Non-linearity limit lines (right-most lines) as shown are for illustrative purposes only. Exact limits depend on number of wavelengths, channel spacing, laser chirp, length of spans between optical amplifiers and the number of spans.

As shown, the dynamic range of the 40 Gbps OOK NRZ option is significantly less than the 10 Gbps option. This results in a significant infrastructure cost increase for the conventional OOK NRZ 40 Gbps solution.

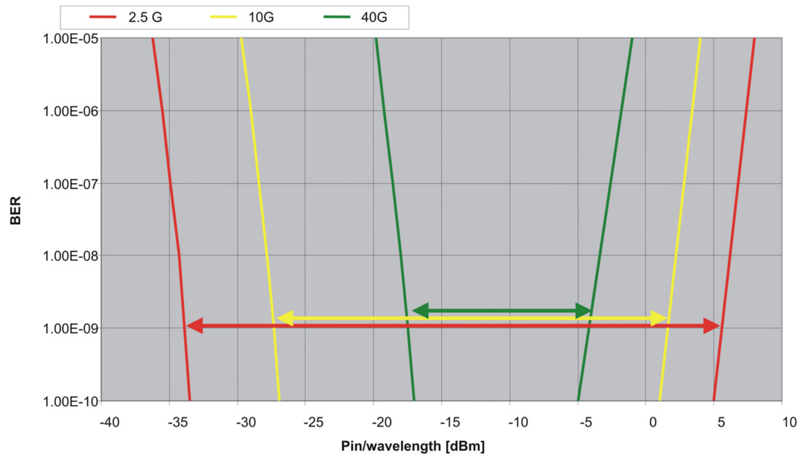


Figure 6. NRZ Modulation Format Power Budget Requirements

Chromatic Dispersion and PMD Limitations

Chromatic dispersion limit, for zero-chirp (externally modulated laser), NRZ modulation, is roughly 1000km for 2.5Gbps, 65km for 10Gbps and only 4 km for 40Gbps, on standard single-mode fibers (SMF-28 is one example.) For directly modulated 2.5Gbps lasers, this limit is at approximately 200km.

Polarization-mode Dispersion (PMD) is proportional to square-root of distance, as well as to square-root of length of Dispersion Compensating Fiber (DCF) used. The PMD graph in Figure 7 assumes that as much contribution to PMD came from DCF, typically 1.0 ps per 100km-compensator, as did from the SSMF itself: 0.1 ps/sqrt(km). The resulting PMD limits are 80,000 km for 2.5Gbps, 5,000km for 10Gbps and only 312 km for 40Gbps.

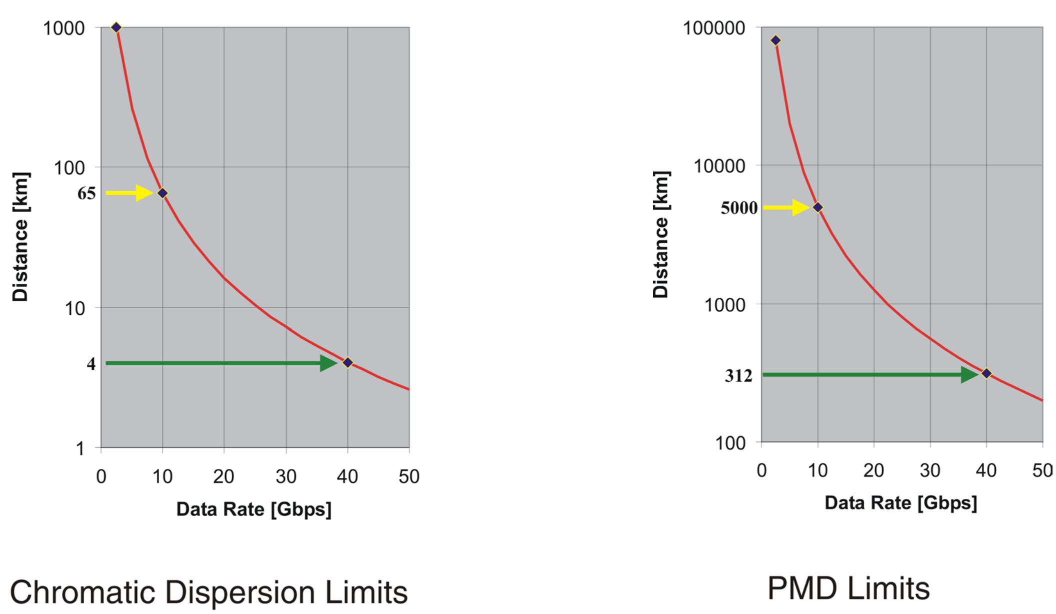


Figure 7. Chromatic Dispersion and Polarization-mode Dispersion Limitations

Fiber Non-linearity Effects

This figure is based on references [Chraplyvy] and [Agrawal]. All curves shown for penalty of 1dB, on a Standard Single Mode Fiber (SSMF), with 0.2 dB/km attenuation, operating in 1550nm range, with 100 GHz channel spacing.

Stimulated Raman Scattering and Stimulated Brillouin Scattering are based on photon/phonon interactions such that power of one wavelength is transferred to other wavelengths or photons traveling in the other direction.

Self Phase Mixing is caused by the change of refractive index of the fiber as a result of the optical field intensity. As a result the velocity of light in the fiber changes with momentary signal power and thus the phase of the of the signal is additionally modulated by the optical power variations. Cross phase modulation is similar but is caused by the power variations of other channels on other wavelengths. Four wave mixing is caused by parametric amplification processes where the fiber non-linearity couples sets of equi-spaced optical frequencies (such as in practical equi-spaced DWDM systems.)

While it is noted in the previous slide that fiber dispersion (CD) is generally responsible for limiting system links, it also significantly reduces fiber non-linearities. Indeed fiber non-linearities are especially dominant in specialty low dispersion fibers and severely limit link lengths. Therefore a proper higher order modulation format that practically overcomes the effect of fiber dispersion (through alternative electronic or optical means) can successfully exploit the fiber dispersion of SSMF fiber to provide superior link performance.

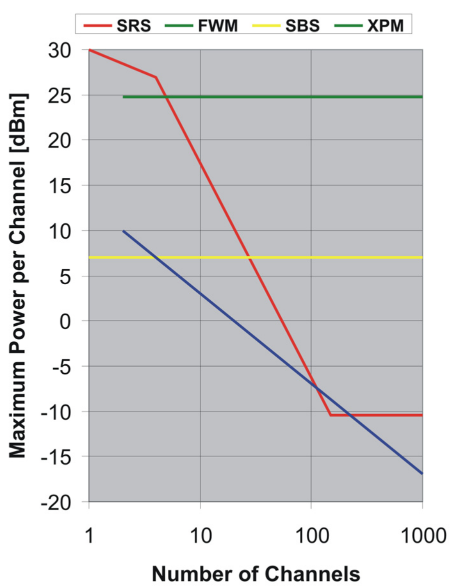


Figure 8. Fiber Non-linearity Effects

Alternative 40 Gbps Solutions

Other modulation formats, essentially optimizing how information is encoded into intensity, phase, frequency, or polarization of a fiber-transmitted optical wave exist.

Some examples of alternative modulation schemes include:

- Solitons
- Coherent transmission
- Sub-Carrier Multiplexing (SCM)
- Chirped Return-to-Zero
- Carrier-Suppressed Return-to-Zero (CS-RZ)
- RZ Differential Phase Shift Keying (RZ-DPSK)

Optical QAM Modulator

This quadrature amplitude modulator (QAM) based link is based on references [OFC 2002 Griffin] and [OFC 2004 Tutorial Gnauck & Winzer]. Continuous Wave (CW) laser output is split into two arms, each feeding a Mach-Zehnder (MZ) modulator. A controllable 90-degree phase shifter in one arm is set to maintain exactly 90 degrees of shift in between the two arms. Combined signals from the two arms are propagated over the fiber, split on the receiver side, each side detected with a differentially-fed balanced receiver.

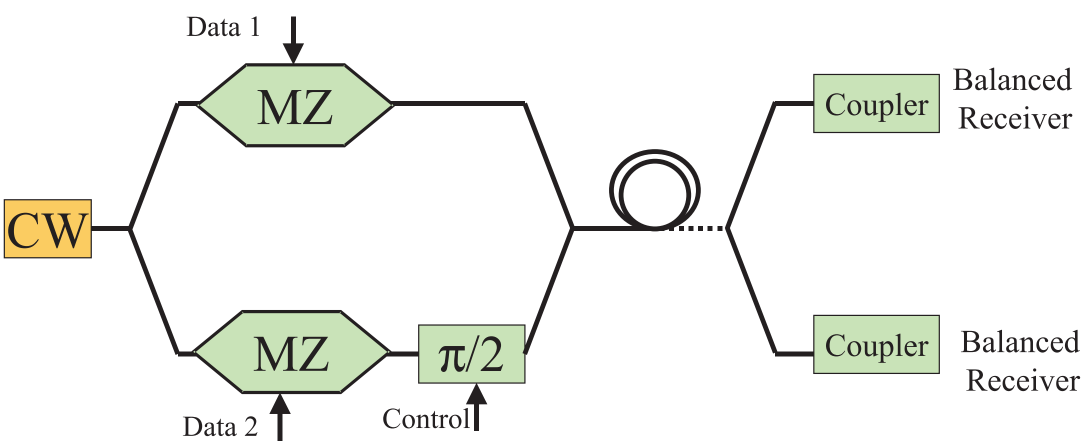
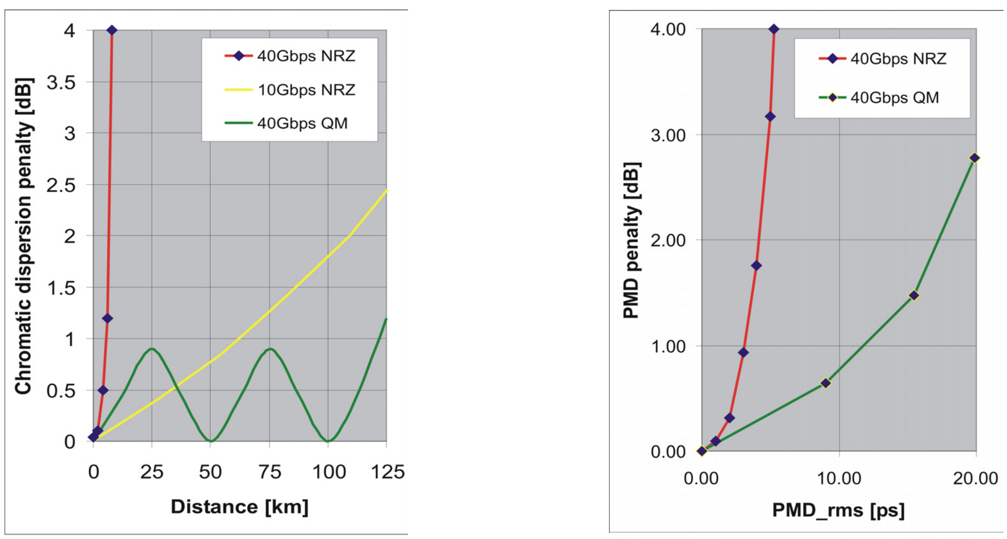


Figure 9. Optical QAM Modulator

CD and PMD Limits, 40 Gbps

The left-hand figure shows chromatic dispersion penalty versus distance of propagation along standard single mode fiber (SSMF). Left-most curve is for 40 Gbps NRZ, it shows 1 dB penalty at only 4 km of SSMF. Yellow curve is for 10 Gbps NRZ, its 1 dB penalty is at 65 km of SSMF. The green curve is for quadrature-based, per-channel electronic dispersion compensated, 40 Gbps modulation format [data kindly provided by Teradvance], where 1 dB power penalty is reached only after 120 km of SSMF.

Right-hand figure shows PMD penalty vs. accumulated RMS PMD value, measured in picoseconds. For 40 Gbps NRZ OOK format, a 1 dB penalty is reached after 2.5ps (10% of bit period), while for quadrature modulation format 1 dB penalty is reached only after 10ps of RMS PMD, therefore matching performance of 10 Gbps systems, in terms of PMD; also per [Teradvance] reference. As shown in Figure 7, a 1 dB penalty at 10 ps of PMD corresponds to the PMD limit at 5,000 km of SSMF.



CD Penalty vs. Distance

PMD Penalty vs. rms PMD

Figure 10. CD and PMD Limits, 40 Gbps

Dynamic Window for Higher Level Modulation Schemes

Solid lines in Figure 11 are those already shown in Figure 6, emphasizing reduction of dynamic range with increase of data rate per wavelength, for OOK NRZ format.

Dotted left-hand side curve is from reference [OFC 2004 Tutorial Gnauck & Winzer] , for 42.7 Gbps, RZ-DPSK, where an EDFA is used as a pre-amplifier – result: sensitivity as good as for APD-based 2.5 Gbps!

Dotted right-hand side curve is from the same reference [OFC 2004 Tutorial Gnauck & Winzer] , for a single 42.7 Gbps channel, 33% RZ-DPSK, for transmission over 24 x 80-km SSMF-spans. Its non-linear performance limit line is on the order on NRZ 10 Gbps limit line.

Resulting dynamic range for this non-OOK 40 Gbps modulation format is comparable to those of 10 Gbps and 2.5 Gbps, therefore allowing for use of 2.5 Gbps / 10 Gbps -intended optical transport infrastructure.

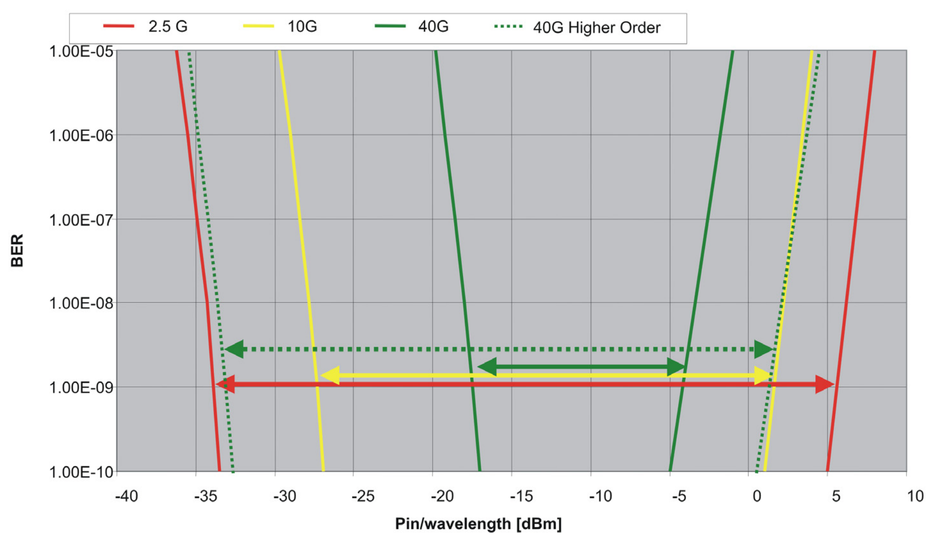


Figure 11. Dynamic Window for Higher Level Modulation Schemes

Conclusion

For initial VOD deployment, 2.5 Gbps transport rate is a cost effective solution. Applying 10 Gbps transport provides significant additional bandwidth to VOD networks for a modest investment in the existing infrastructure. For VOD networks that expect high digital penetration and HDTV request rates, higher order modulation schemes that allow 40 Gbps transport over current infrastructure are a cost effective choice.

References

[1] Govind P. Agrawal, ”Fiber-Optic Communication Systems”, Second Edition, Willey Interscience, 1997

[2] Alan H. Gnauck and Peter J Winzer, “Phase-Shift-Keyed Transmission”, tutorial notes “TuF5” from Optical Fiber Communications (OFC) Conference, February 2004, Los Angeles, CA

[3] Andrew R. Chraplyvy, “Limitations on Lightwave Communications Imposed by Optical-Fiber Nonlinearities” (invited paper), IEEE Journal of Lightwave Technology, Vol. 8, No. 10, October 1990, pages 1548-1556

[4] R. A. Griffin, R. I. Johnstone, R. G. Walker, J. Hall, S. D. Wadsworth, K. Berry, A. C. Carter, M. J. Wale, J. Hughes, P. A. Jerram and N. J. Parsons, “10Gbps Optical Differential Quadrature Phase Shift Key (DQPSK) Transmission using GaAs/AlGaAs Integration”, OFC Post-deadline Paper, March 2002, Anaheim, CA

[5] Venkatesh G. Mutalik, “DWDM: Matching Technology Advancements with Business Requirements”, National Cable Telecommunications Association (NCTA) Proceedings, June 1999

[6] Teradvance Communications models and test results for chromatic dispersion and PMD penalty versus distance for a proprietary quadrature-based 40 Gbps modulation format

[7] L. D. Garret, R. W. Tkach, L. E. Nelson, A. R. Chraplyvy, “Performance of 8 x 2.5 Gbit/s transparent optical network versus EDFA power level”, OFC ’98

[8] M. Cvijetic, “Progress Toward Multi-Band High Capacity WDM Systems, (invited paper), IEEE LEOS, November 2001, San Diego, CA