Vestigial Side Band Demultiplexing for High Spectral Efficiency WDM systems

By

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Outline

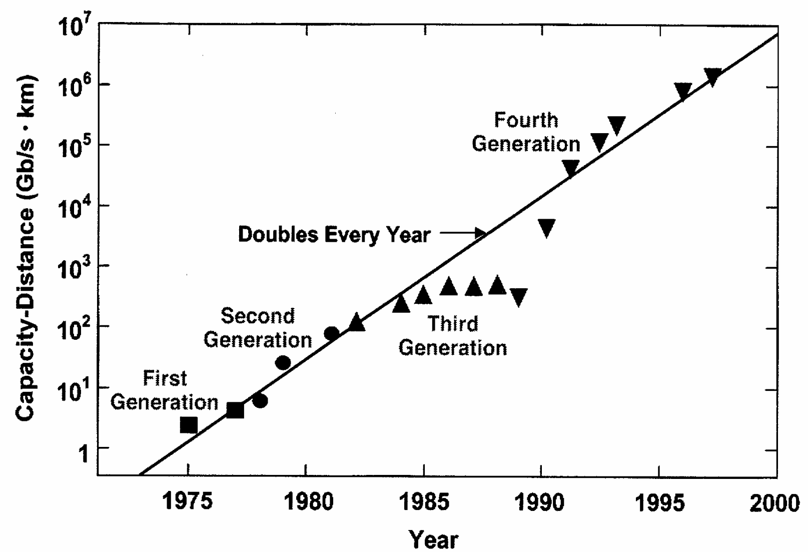
- Introduction
- Signal propagation in optical fibers
- FiberSim – Fiber Optic Simulator
- Increasing spectral efficiency in WDM systems
- Modeling of a reported experimental 40 Gbit/s VSB demultiplexing system
- Analysis of simulation parameters using FiberSim
- Design of a 10 Gbit/s VSB demultiplexing system with 0.8 bit/s/Hz spectral efficiency
- Conclusion and Future work

Introduction

- Fiber-optic communication was born with the invention of laser in 1960 and the use of optical fiber in 1966 for guiding the light.

- Enormous progress realized over the past 30 years in fiber-optic communication systems that can be grouped into several distinct generations.

- Current emphasis on lightwave systems is on increasing the channel capacity by
  - Extending the wavelength range of operation
  - Increasing the spectral efficiency



- Spectral efficiency is the ratio of average channel bit rate to the average channel spacing.

Signal propagation in Optical Fibers

- Fiber Characteristics
  - Attenuation $$P(z) = P(0).e^{-\alpha_p z}$$
  - Dispersion $$\beta(\omega) = n(\omega)\frac{\omega}{c} = \beta_0 + \beta_1(\omega-\omega_0) + \frac{1}{2}\beta_2(\omega-\omega_0)^2 + \frac{1}{6}\beta_3(\omega-\omega_0)^3 \ldots\ldots\ldots$$ $$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2$$
  - SPM and XPM
  - FWM $$\mathrm{f_{ijk}} = \mathrm{f_i} + \mathrm{f_j} - \mathrm{f_k} \text{ with } i, j \neq k$$
  - SRS
- Nonlinear Schrodinger wave equation
  - Mathematical representation of nonlinear propagation of light signal through a fiber

$$\frac{\partial A}{\partial z} + \beta_1\frac{\partial A}{\partial t} + \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2} - \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^3} + \frac{\alpha}{2}A = i\gamma|A|^2 A \qquad \text{where} \quad \gamma = \frac{n_2\omega_0}{c.A_{eff}}$$

Signal propagation in Optical Fibers (contd.)

- Propagation equation including delayed and cross polarized components

$$\frac{\partial A_i}{\partial z} + \frac{1}{2} j\beta_2 \frac{\partial^2 A_i}{\partial T^2} - \frac{1}{6}\beta_3 \frac{\partial^3 A_i}{\partial T^3} + \frac{\alpha}{2} A_i = j(1-f_R)\gamma\left(|A_i|^2 + \frac{2}{3}|A_{3-i}|^2\right)A_i + \frac{1}{3} j(1-f_R)\gamma A_i^* A_{3-i}^2 \exp(-j2\Delta\beta z)$$

$$+ jf_R\gamma A_i(t)\int_0^\infty |A_i(t-s)|^2 h_r(s)ds + \frac{1}{3} jf_R\gamma A_i(t)\int_0^\infty |A_{3-i}(t-s)|^2 h_r(s)ds$$

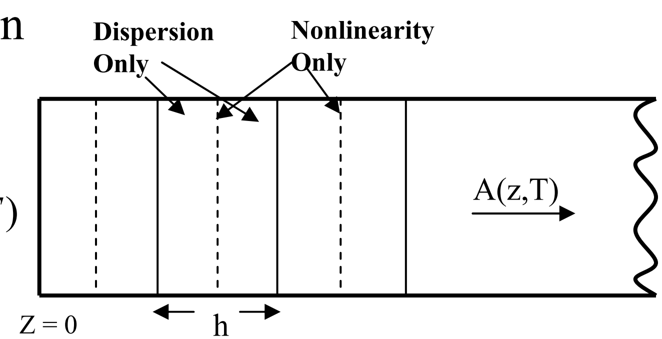
$$+\frac{1}{3} jf_R\gamma A_{3-i}(t)\exp[-j2\Delta\beta z]\int_0^\infty A_i^*(t-s)A_{3-i}(t-s)h_r(s)ds + \frac{1}{3} jf_R\gamma A_{3-i}(t)\int_0^\infty A_i(t-s)A_{3-i}^*(t-s)h_r(s)ds$$

where Raman response function $h_r(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1.\tau_2^2}.\exp\left(-\frac{t}{\tau_2}\right).\sin\left(\frac{t}{\tau_1}\right)$

- Split step Fourier transform method
  - Numerical approach to solve propagation equation

$$\frac{\partial A}{\partial z} = (D_s + N_s)A$$

$$A(z+h,T) \cong \exp\left(\frac{h}{2}D_s\right).\exp\left(\int_z^{z+h} N_s(z')dz'\right).\exp\left(\frac{h}{2}D_s\right).A(z,T)$$



Evaluation of Nonlinear terms

- Nonlinear terms contain convolution integrals of the form $\int_0^\infty f(t-\tau).h_r(\tau).d\tau$ which can be evaluated using the following methods

  - Direct Integration method

  - Moments method

$$f(t-\tau) = f(t) - \tau \frac{\partial}{\partial t} f(t) + \frac{\tau^2}{2}\frac{\partial^2}{\partial t^2} f(t) - ....$$

$$\int_0^\infty f(t-\tau).h_r(\tau).d\tau = \tau_R^0 f(t) - \tau_R^1 \frac{\partial}{\partial t} f(t) + \frac{1}{2}\tau_R^2 \frac{\partial^2}{\partial t^2} f(t) - .....$$

  - FFT method

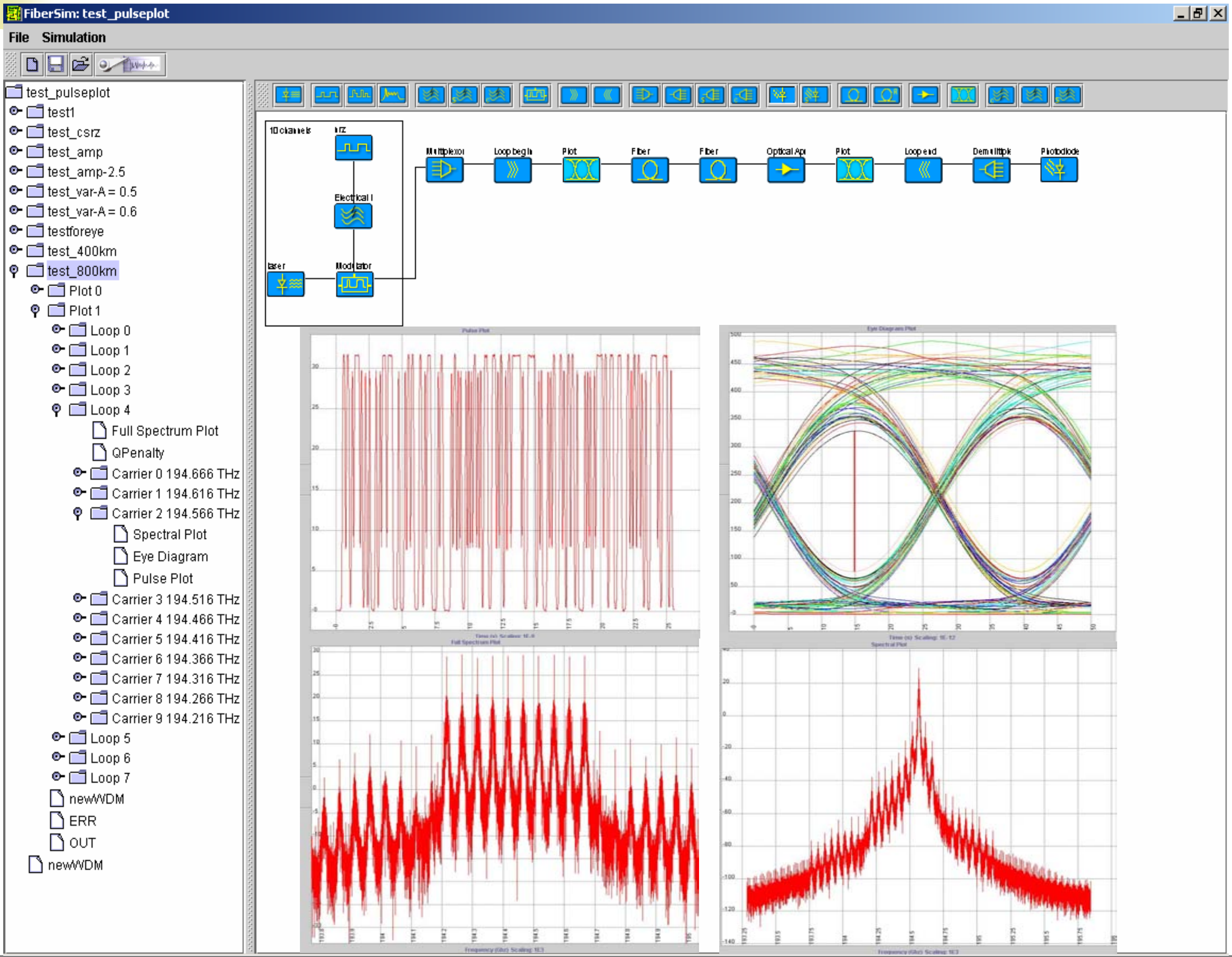
$$\int_0^\infty f(t-\tau).h_r(\tau).d\tau = FFT^{-1}\{F(\omega).H_r(\omega)\}$$

FiberSim

- FiberSim – numerical simulations based Fiber Optic Simulator developed at ITTC, University of Kansas.
  - Capable of modeling all major fiber properties
  - To model WDM systems
  - Verifies link design at sampled signal level

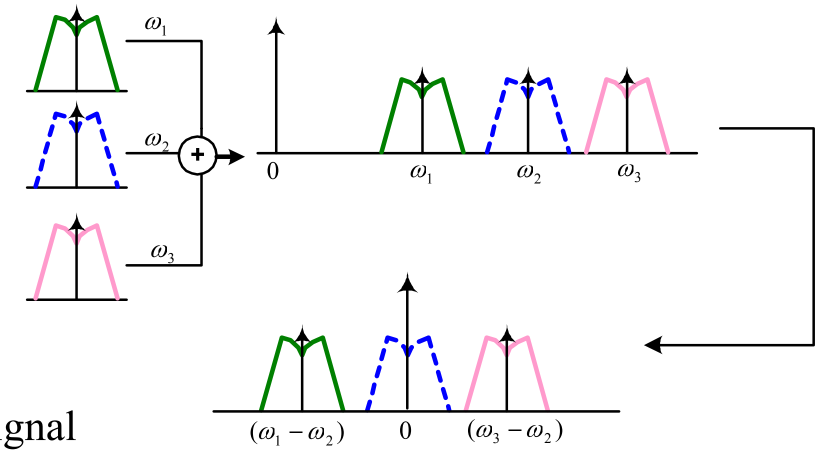
- Modules in FiberSim
  - Transmitter (Data generator, Electrical Filters, Laser, Modulator, Multiplexer)
  - Receiver (Demultiplexer, Photodiode, Electrical and Optical Filters)
  - Transmission media (Fiber, Optical Amplifier)

FiberSim GUI and Output



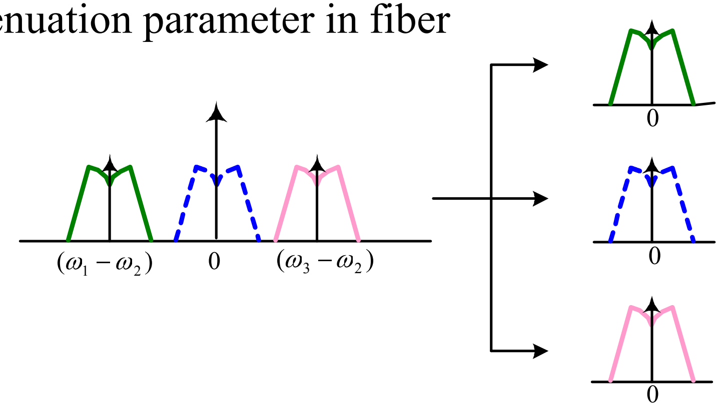
Optical components in FiberSim

- Data Generators
  - NRZ, RZ, CS-RZ
- Electrical Filters
  - Bessel, Butterworth, Ideal, Notch filters
- Optical Sources
  - Lasers modeled as CW source with zero linewidth
- Optical Modulators
  - Ideal Modulator
  - Mach-Zehnder Modulator
- Optical Multiplexers
  - Adds individual channels to form composite signal



Optical components in FiberSim (contd.)

- Optical Fibers
  - Models the attenuation, dispersion, polarization, and nonlinear characteristics of fiber
  - Input parameters: length, attenuation, dispersion, dispersion slope, zero dispersion wavelength, PMD value, core effective area etc.
- Optical Amplifiers
  - EDFA
    - Flat gain amplifier that uses equivalent noise bandwidth model
  - Raman amplifier
    - Raman pumps induce gain by modifying attenuation parameter in fiber
- Optical Filters and Demultiplexers
  - Bessel, Butterworth, Ideal and Notch filters



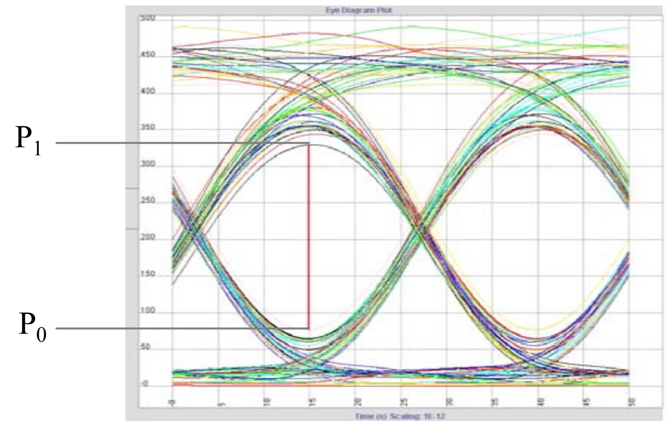
- Optical Detectors
  - Ideal Photodiode at 273 K

Q and BER calculation in FiberSim

- BER is calculated from Q factor

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}} \frac{\exp(-Q^2)}{Q}$$

$$Q = \frac{I_1 - I_0}{\sqrt{\sigma_1^2} + \sqrt{\sigma_0^2}} \quad \text{where } I_1 = RP_1 \;,\; I_0 = RP_0$$

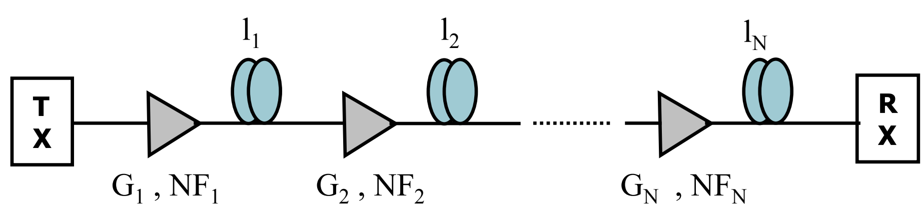


The various noise types considered are

- signal-spontaneous noise
- spontaneous-spontaneous noise
- shot-spontaneous noise
- shot noise
- thermal noise

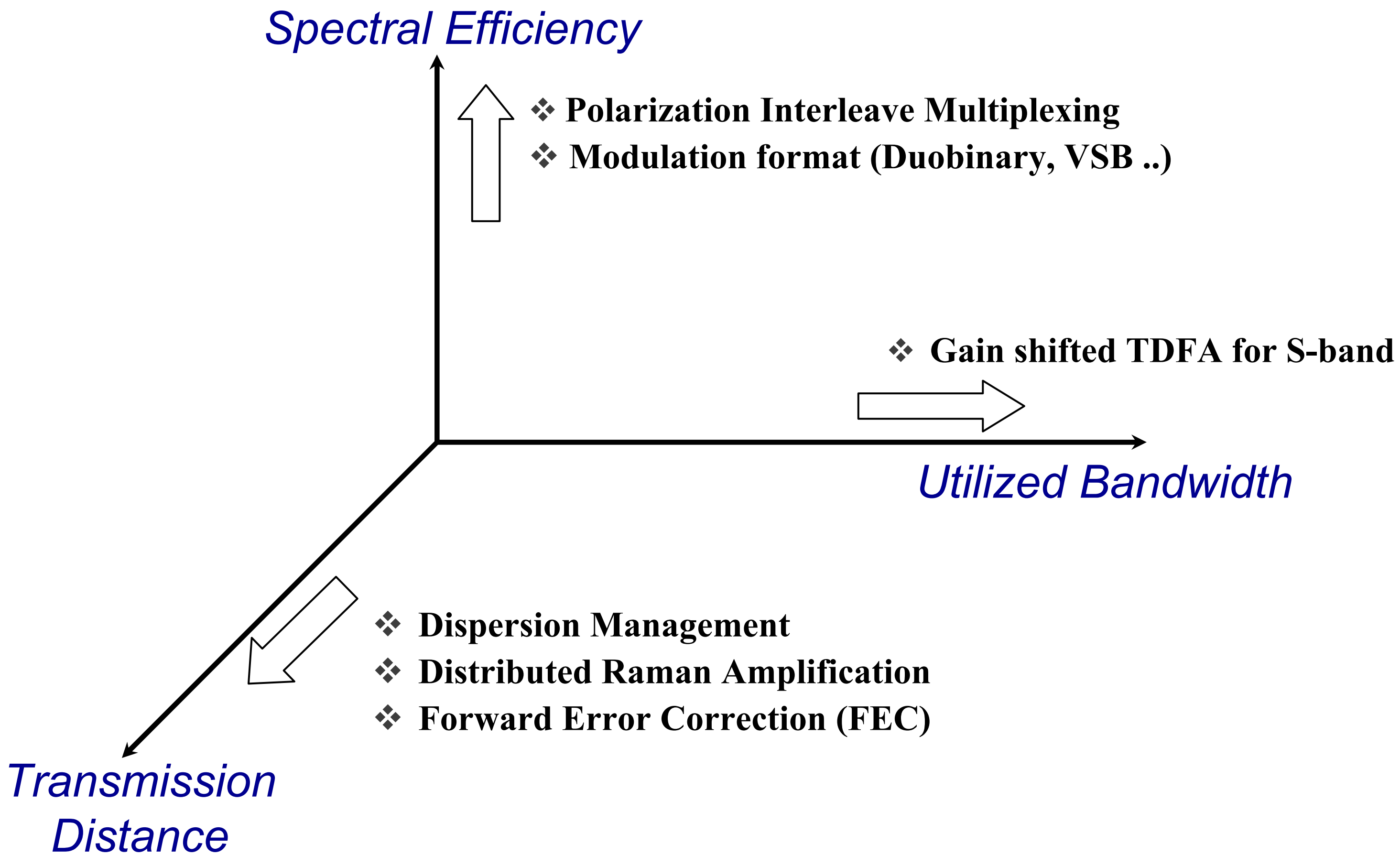
Noise variances are calculated from noise power spectral density given by

$$S_{sp} = \frac{1}{2} h\nu \sum_{i=1}^{N} (NF_i) G_i L_i$$



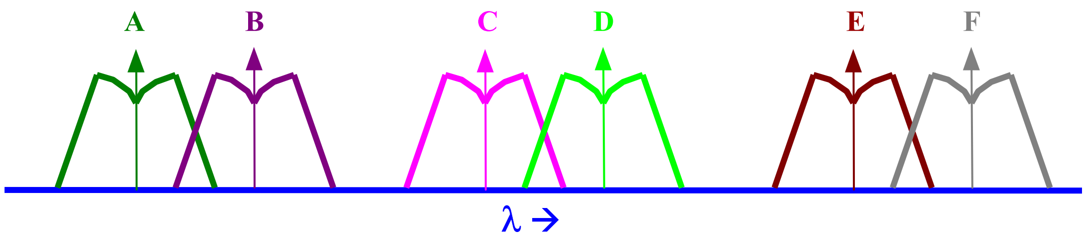
Increasing system capacity and transmission distance

- Growing demand for bandwidth in fiber-optic networks can be addressed by designing WDM systems with multi-terabit capacity



VSB Demultiplexing

- Channels are spaced with alternating wide and narrow spacing

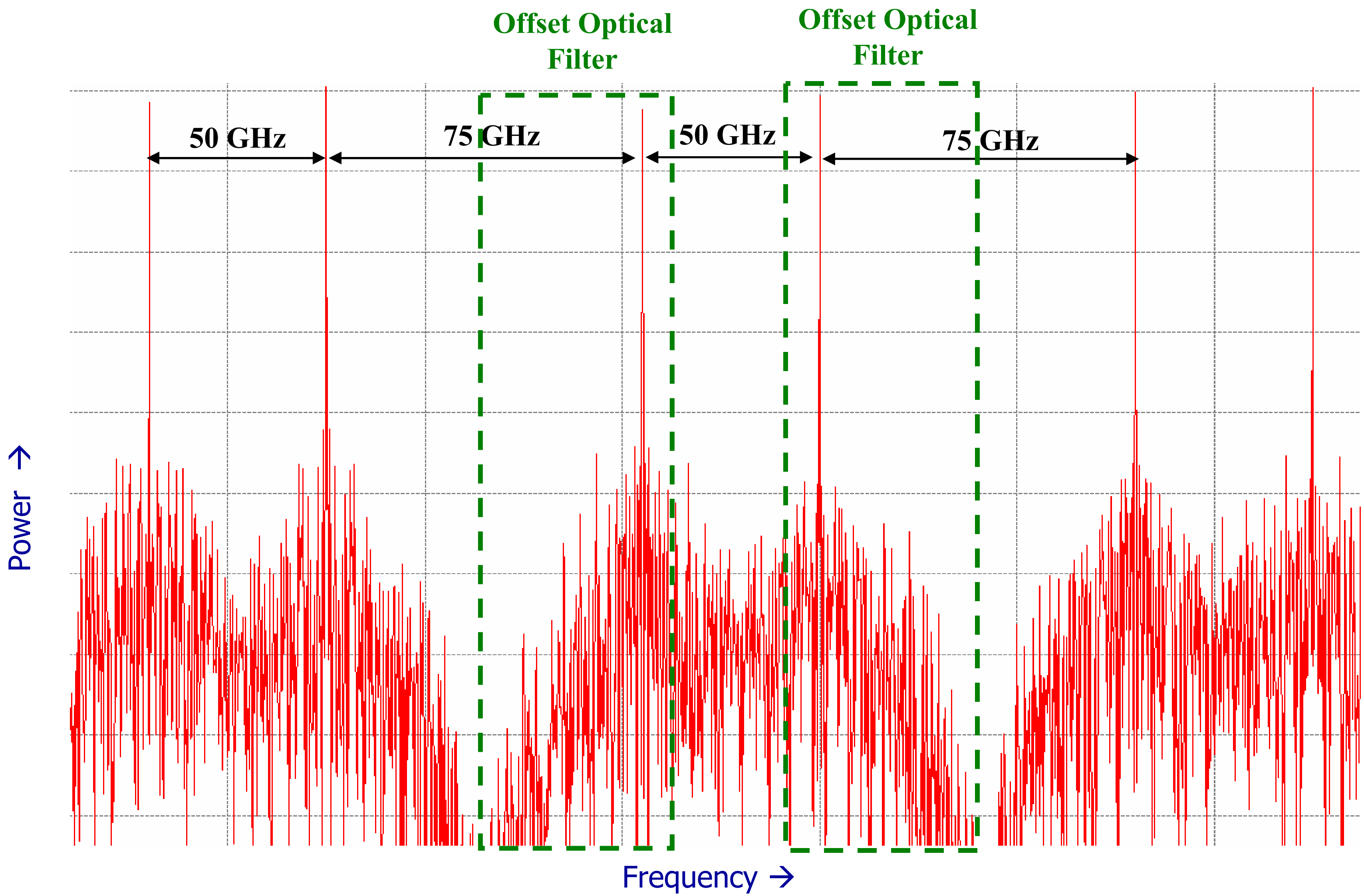


- Filter out the sideband experiencing smallest overlap with the adjacent channels and ignore the other sideband of channel at receiver

- VSB-like filtering of the channel performed at the receiver

- A 40 Gbits VSB demultiplexing Alcatel experimental system used
  - Channel spacing scheme – Alternatively spaced 75 Ghz and 50 Ghz channels
  - Optical demultiplexing filters – 60 GHz optical BW with 20 GHz offset frequency

VSB Demultiplexing (contd.)



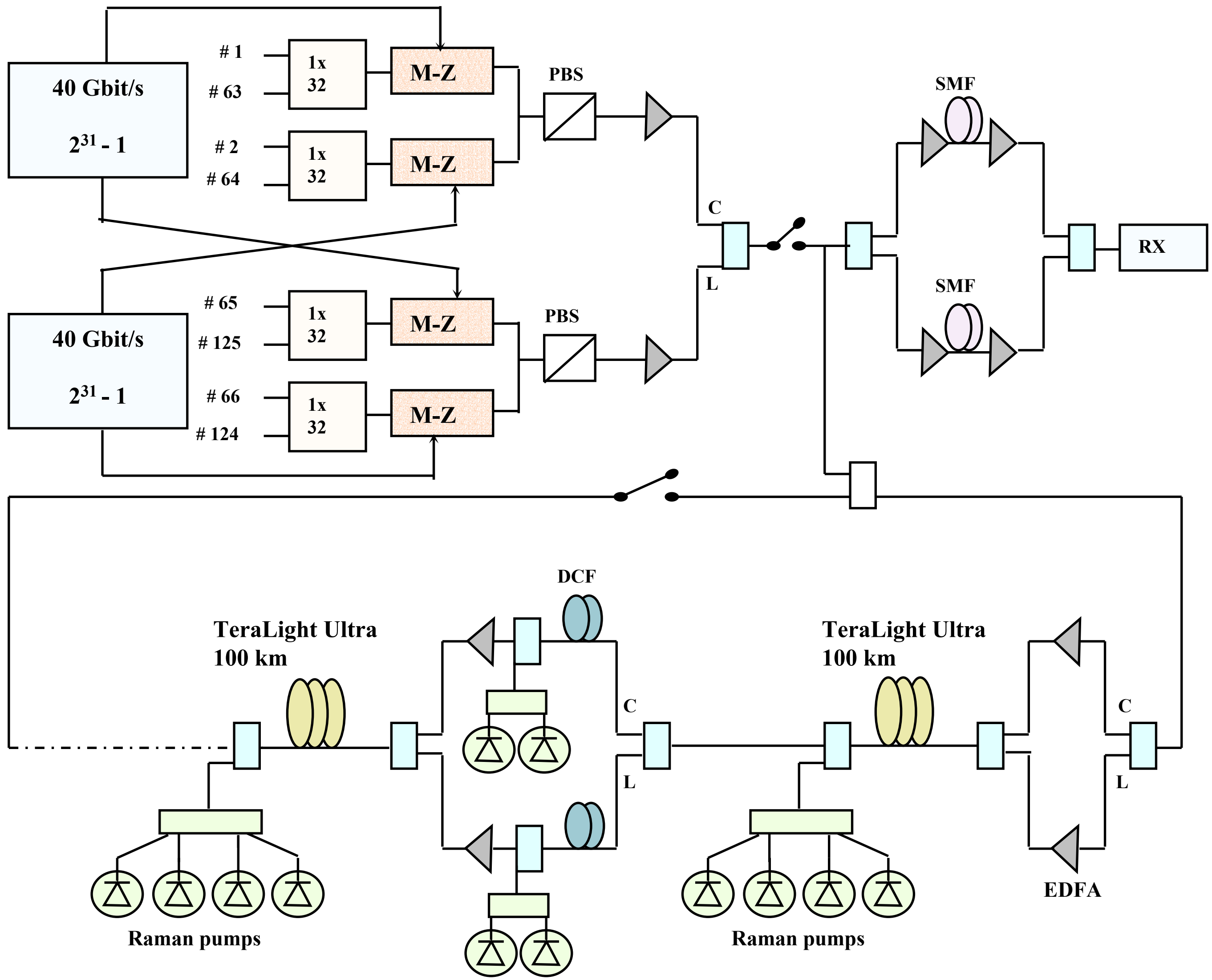
Alcatel Experimental System

- Alcatel reported a VSB demultiplexing WDM system with 5 Tbit/s capacity over 1200 km of Teralight Ultra fiber with 0.64 bit/s/Hz spectral efficiency

  - Transmitter parameters
    - 125 channels spread across C-band and L-band
    - 40 Gbit/s using NRZ format
    - Alternating 50 GHz and 75 GHz channel spacing
    - Polarization interleave multiplexing
    - Channel launch power: - 2 dBm (0.631 mW)

  - 1200 km of Teralight Ultra fiber
    - Attenuation 0.20 dB/km
    - 8.0 ps/nm.km and 0.052 ps/nm^2.km dispersion at 1550nm
    - PMD value 0.04 $ps/\sqrt{km}$

Alcatel Experimental System (contd.)



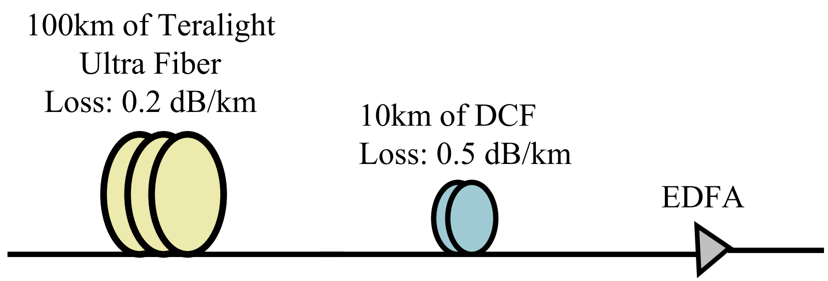
Alcatel Experimental System (contd.)

- DCFs
  - - 80.0 ps/nm.km and - 0. 52 ps/nm^2.km dispersion at 1550nm
  - Accumulated dispersion not made to exceed 20 ps/nm per span in the C-band and 25 ps/nm per span in the L-band
- Raman amplification
  - 15 dB gain in Teralight Ultra fiber using Raman pumps at 1427 nm, 1439 nm, 1450 nm and 1485 nm
  - 8 dB gain in DCF using Raman pumps at 1423 nm and 1455 nm in the C band and 1470 nm and 1500 nm in the L band
- EDFAs: 2 dB in the C-band and 1 dB in the L-band to mitigate SRS
- Demultiplexer optical filter with 60 GHz bandwidth

➢ The measured BERs at the end of 1200 km, with FEC, was always better than 10^{-13} , which corresponds to a Q value of 8 dB.

Issues in modeling Alcatel Experimental system

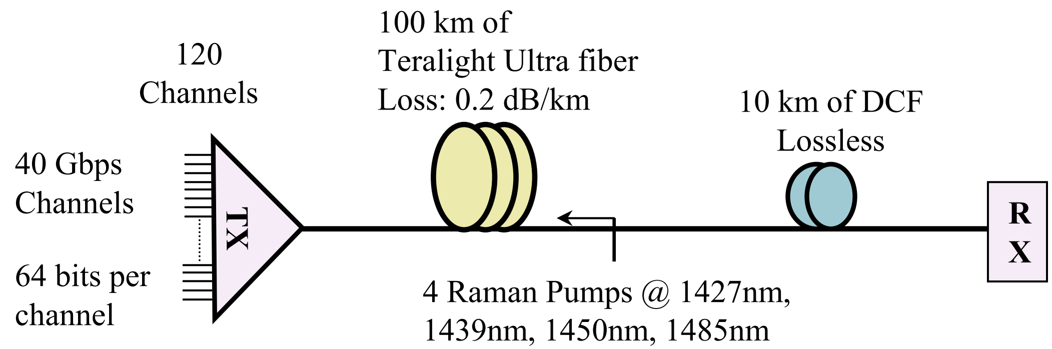
- Raman pump power values, which are required for Raman noise characteristics evaluation, are not specified
- Simulating the characteristics of 1200 km of Raman amplified fiber takes very long time
  - Fiber-EDFA equivalent model for a Raman amplified system developed



Loss per component:	20 dB	5 dB	
Gain per component:	15 dB	8 dB	2 dB
Net Gain per component:	-5 dB	3 dB	2 dB

Raman pump powers evaluation

- FiberSim used to find Raman pump powers that induce 15 dB gain in 100 km of Teralight Ultra fiber.

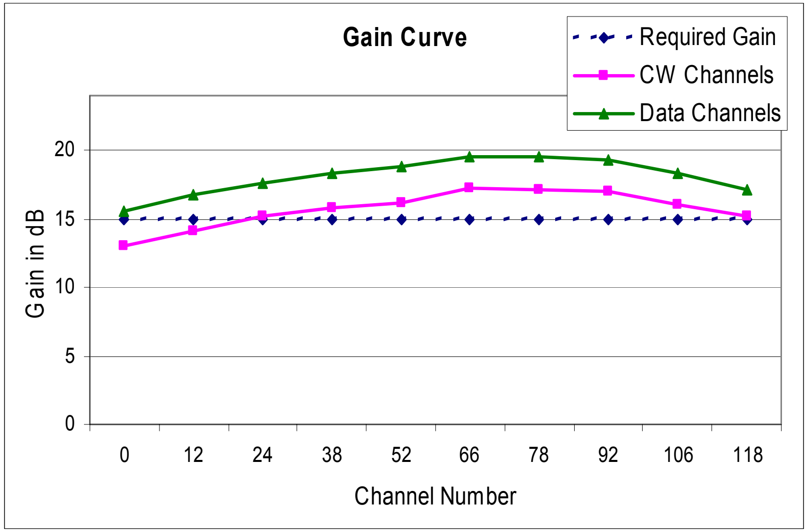


$$Gain(dB) = Attenuatio\,nParameter * Length + 10 * \log\left(\frac{P_{avg,out}}{P_{avg,in}}\right)$$

- From simulations, the required pump powers are found to be

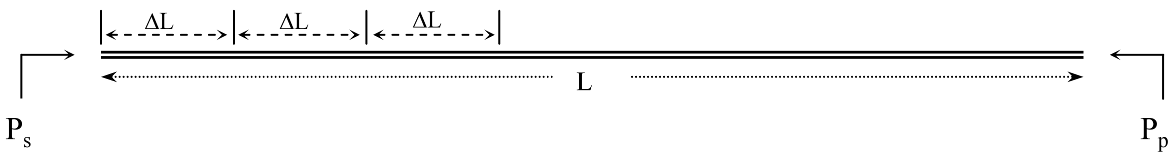
  60 mW at 1427 nm , 60 mW at 1439 nm,

  55 mW at 1450 nm , 55 mW at 1485 nm



Modeling Raman gain characteristics

- Break down fiber into smaller sections each with an effective attenuation parameter



$$I_s(\Delta L) = I_s(0)\exp\{g_R I_0(\Delta L) L_{eff} - \alpha.\Delta L\}$$

$$L_{eff} = \frac{1}{\alpha}\left[1 - \exp\{-\alpha.\Delta L\}\right]$$

where $$I_s(0) = \frac{P_s}{A_{eff}}$$

$$I_0(\Delta L) = \frac{P_p}{A_{eff}}\exp\{-\alpha.(L - \Delta L)\}$$

Effective attenuation parameter of n^th section $$\alpha_{eff}(n) = \frac{I_s(n\Delta L)}{I_s((n-1)\Delta L)}$$

α_{eff} in dB/km in the 10 sections of 100km Teralight Ultra fiber

	For P_p = 112.5mW
	0.1911
	0.1859
	0.1777
	0.1647
	0.1441
	0.1113
	0.0595
	- 0.0227
	- 0.1529
	- 0.3593
Net loss over 100 km of fiber in dB	4.995

Modeling Raman noise characteristics

- In FiberSim Raman noise characteristics is modeled using an EDFA with 0 dB gain and an equivalent Raman noise figure value

$$ENF = \frac{1 + N_{R_j}}{G_{R_j}}$$

where

Photon number of amplified spontaneous Raman scattering noise

$$N_{R_j} = K\left\{G_{R_j}\exp(-\alpha L) - 1 + \frac{K}{q_j}\left(G_{R_j} - 1\right)\right\}$$

Raman on-off gain of the jth channel

$$G_{R_j} = \exp\left\{\frac{q_j}{K}\left[1 - \exp(-\alpha L)\right]\right\}$$

Weighted gain coefficient

$$q_j = \sum_i \frac{g_{ij} P_{piL}}{\alpha}$$

K → Polarization factor,

P_{piL} → Launch power level of ith pump

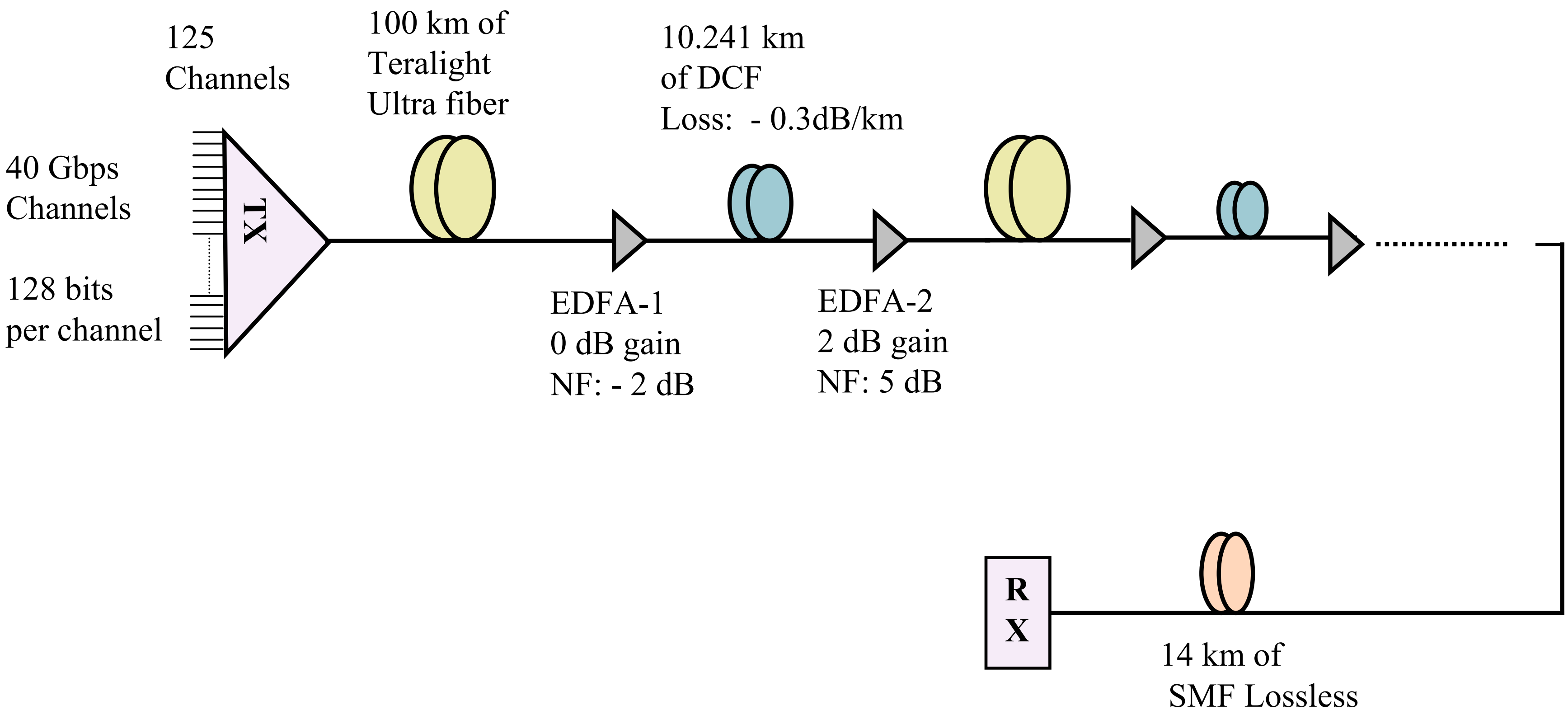
g_{ij} → Raman gain coefficient corresponding to ith pump and jth signal

α → attenuation parameter,

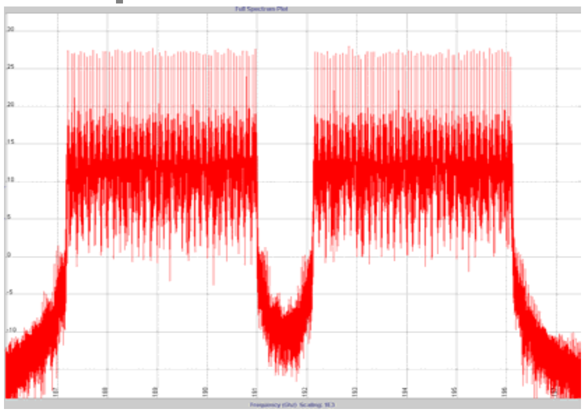
L → Length of Raman fiber,

- Average ENF for Raman amplifier in experimental system is – 2.0 dB

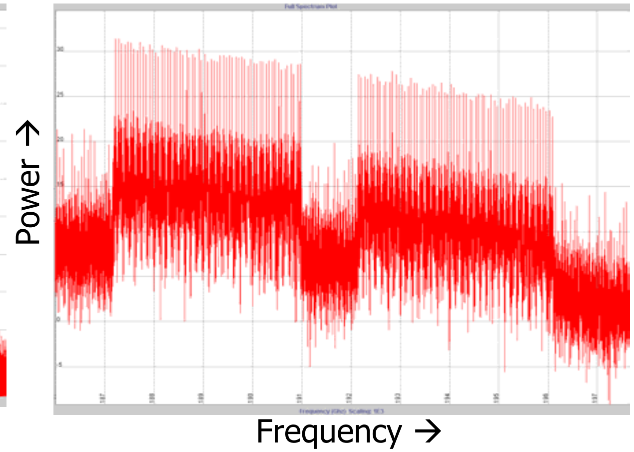
Simulation model for experimental system



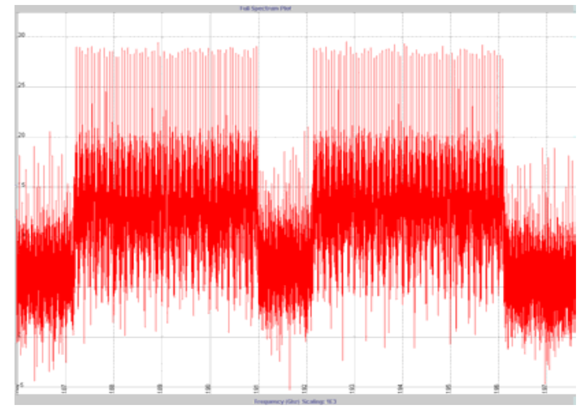
Effect of amplifier gain tilt



Channel spectrum at launch
Channel launch power: 0.35 mW



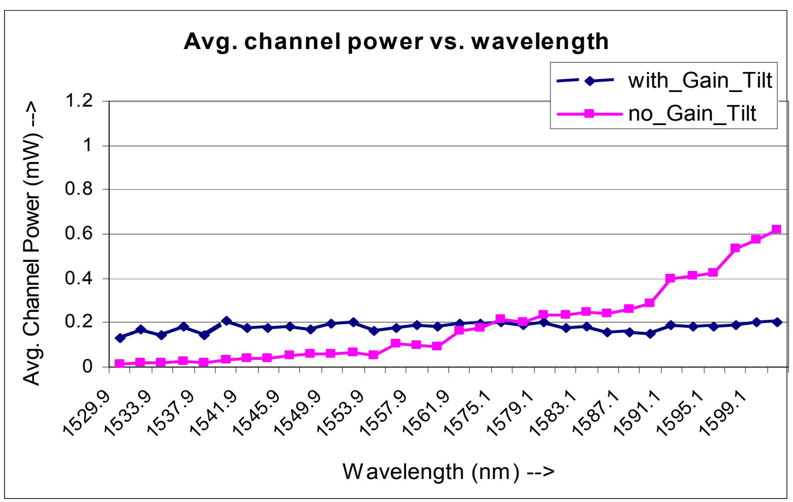
Channel spectrum at end of 1200 km using flat gain EDFA



Channel spectrum at end of 1200 km using tilted gain EDFA

- SRS mitigation using an EDFA with tilted gain profile

- EDFA with positive gain slope with respect to frequency to provide higher gain to high frequency channels



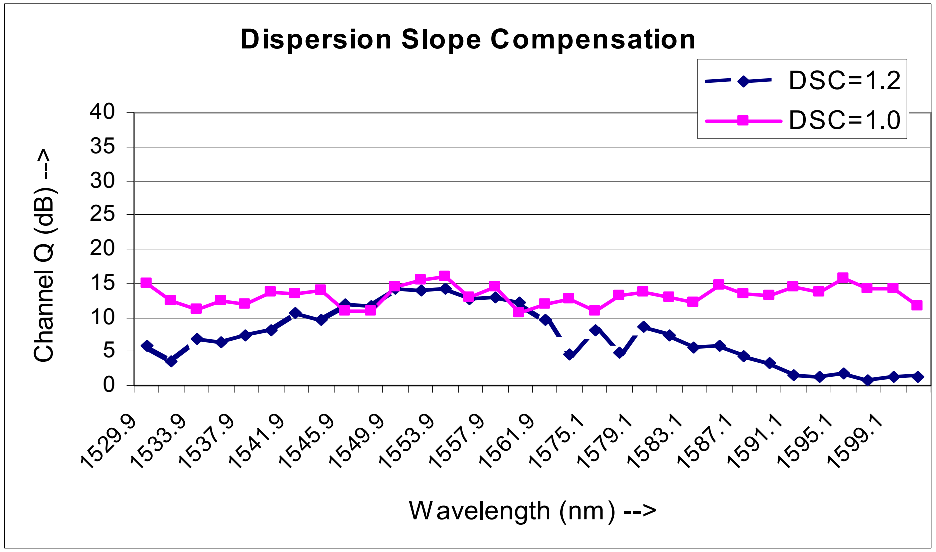
Average Channel power at the end of 1200 km

Effect of dispersion slope compensation

- Dispersion slope compensation is used to provide nearly identical dispersion compensation for all the channels

$$DSC = \frac{D^{1550}_{Fiber} / S^{1550}_{Fiber}}{D^{1550}_{DCF} / S^{1550}_{DCF}}$$

	Fiber	DCF1	DCF2
Dispersion (ps/nm.km)	8.0	- 80.0	- 80.0
Dispersion slope (ps/nm^2.km)	0.052	- 0. 60	- 0. 52
		(DSC = 1.2)	(DSC = 1)

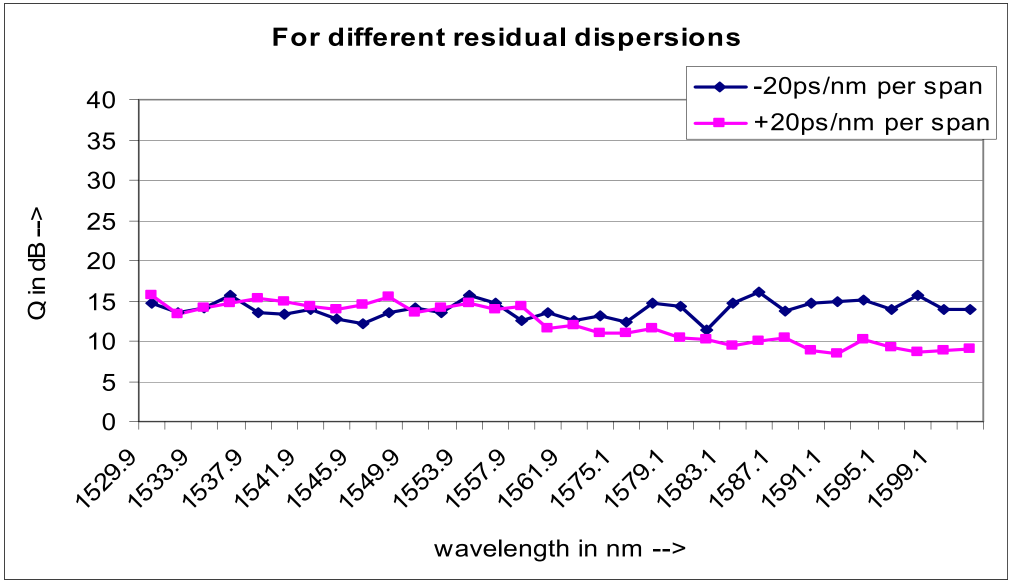


System performance at the end of 1200 km with and without dispersion slope compensation

Effect of residual dispersion

- Complete dispersion compensation per span enhances the effects of nonlinearities in the fiber.

- Over compensation of dispersion, which results in a negative residual dispersion per span, enhances system performance in tightly spaced WDM systems

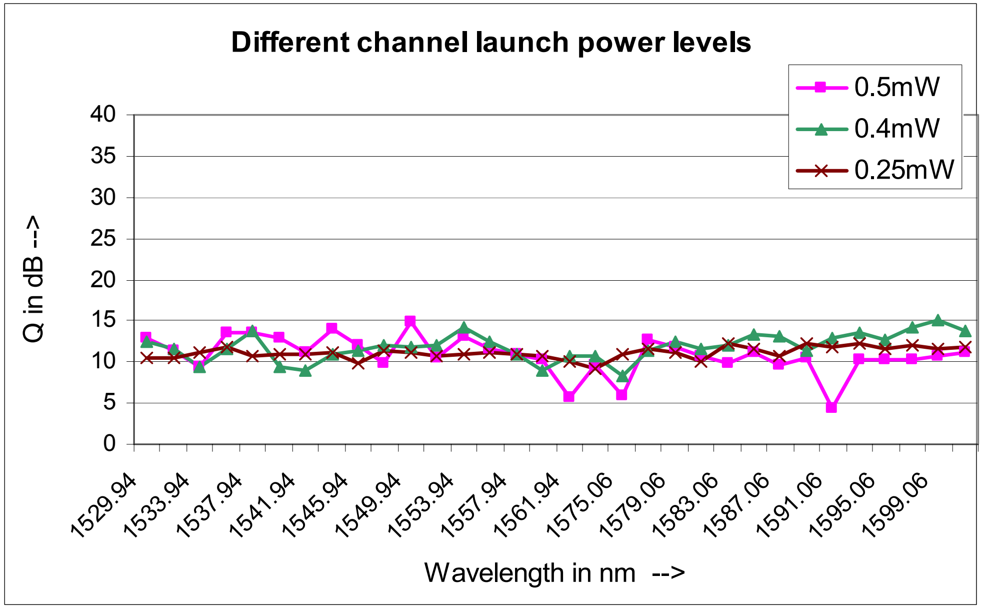


System performance at the end of 1200 km for different residual dispersion schemes

Effect of channel launch power

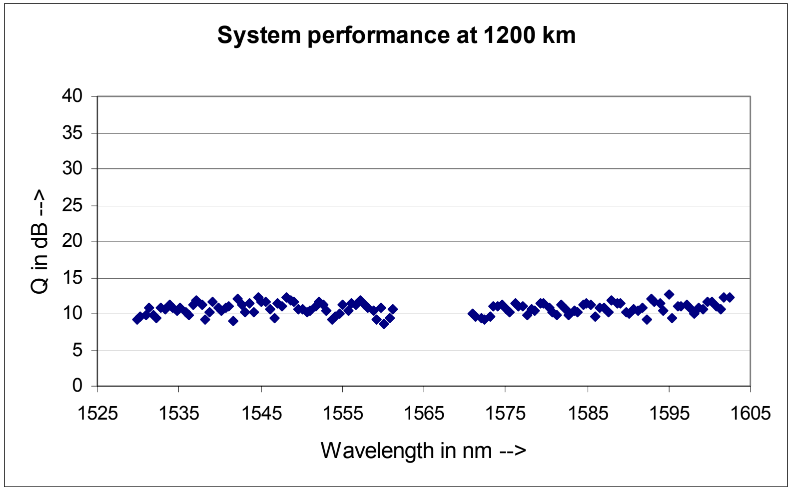
- Channel launch is chosen to balance the effects of fiber nonlinearities and signal to noise ratio of the optical signal.

- The optimal channel launch power is found to be - 6.02 dBm (i.e. 0.25 mW)



System performance at the end of 1200 km for different channel launch powers

Comparison of experimental and simulated results



Q values of all 125 channels at the end of 1200 km – Simulation result

- Experimental system used – 2.0 dBm channel launch power and the channel Qs at the end of 1200 km of fiber were around 8 dB

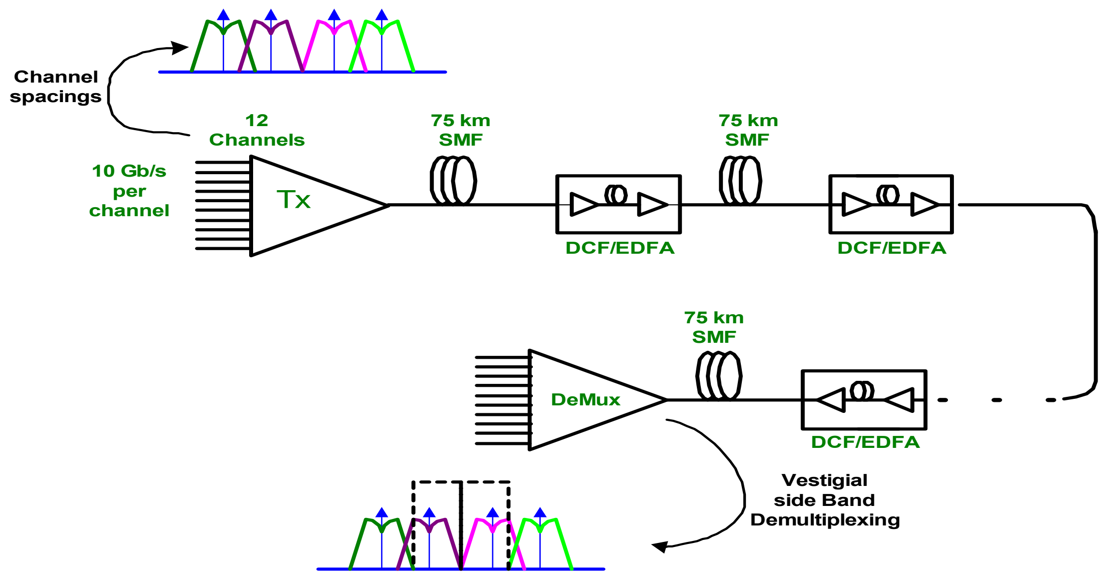
- Simulated system optimal channel launch power is found to be – 6.02 dBm
  - The 4 dB difference between the results could be due to the multiplexing and connector losses in experimental system.

- Channel Qs of the simulated system are around 10 dB
  - The higher Q values can be attributed to the idealistic nature of the simulator

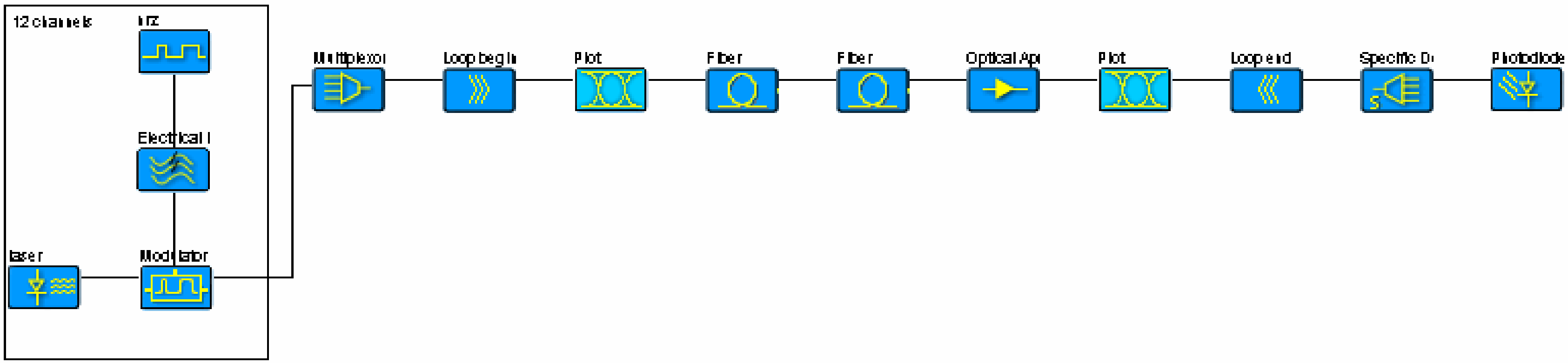
10 Gbit/s WDM system with 0.8 bit/s/Hz spectral efficiency

- High bit rates like 40 Gbit/s introduce new problems in WDM systems
  - Reduction of dispersion tolerance
  - Increased PMD and nonlinearity effects
  - Need for costly high frequency equipment

- Attempt to design a 10 Gbit/s WDM system that utilized VSB demultiplexing to achieve a spectral efficiency of 0.8 bit/s/Hz



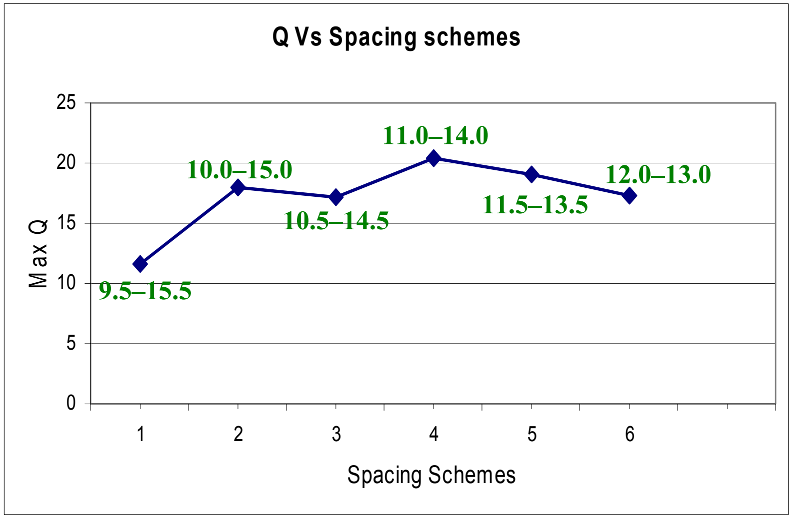
10 Gbit/s WDM system with 0.8 bit/s/Hz spectral efficiency (contd.)



- Transmitter parameters
  - 12 channels at 10 Gbit/s with polarization interleave multiplexing
  - 256 bits per channel generated pseudo-randomly
- 75 km spans of standard SMF
  - Attenuation: 0.25 dB/km
  - Dispersion parameters: 16.7 ps/nm.km & 0.09 ps/nm^2.km at 1550 nm
- DCF
  - Dispersion parameters: - 104.5 ps/nm.km and -1.0 ps/nm^2.km at 1550nm
- EDFA with 18.75 dB gain and Noise figure value of 6.0 dB

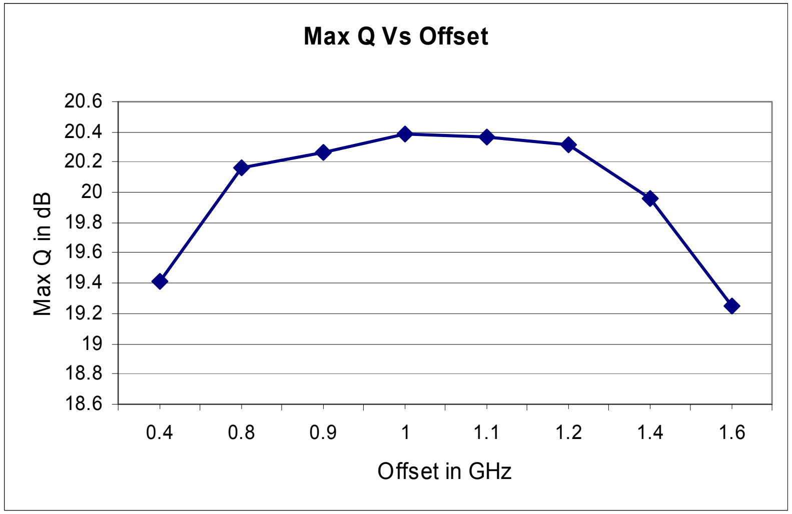
10 Gbit/s WDM system with 0.8 bit/s/Hz spectral efficiency (contd.)

- Optimal channel spacing scheme
  - Average channel spacing of 12.5 GHz
  - Best performance obtained from alternating 11 GHz and 14 GHz spacing scheme



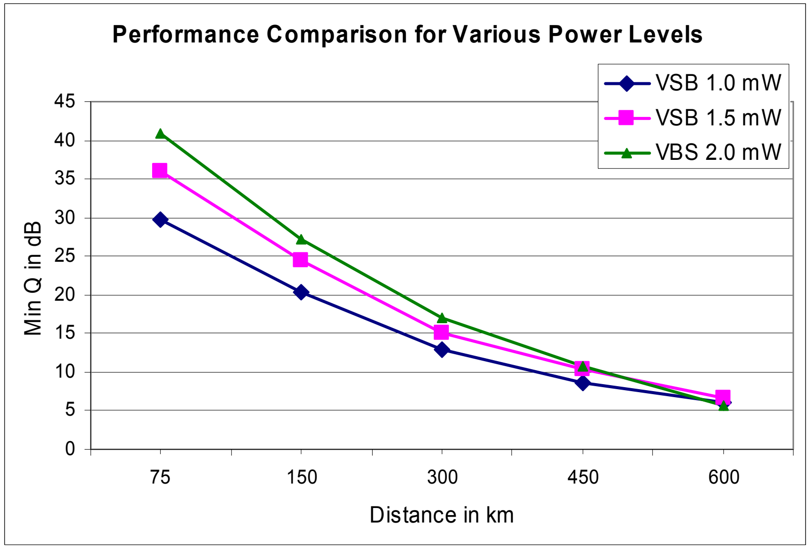
Q measured at a distance of 150 km.
Channel launch power used is 1.5mW

- Optimal Demultiplexer optical filter parameters
  - 3rd order Butterworth filter
  - Optical bandwidth of 12 GHz and offset frequency of 1 GHz



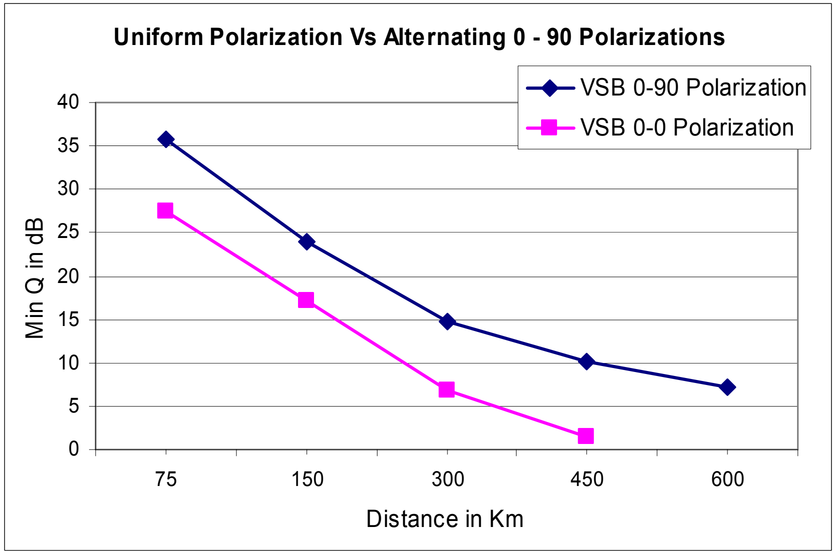
10 Gbit/s WDM system with 0.8 bit/s/Hz spectral efficiency (contd.)

- Optimal channel launch power is found to be 1.761 dBm (i.e. 1.5 mW)



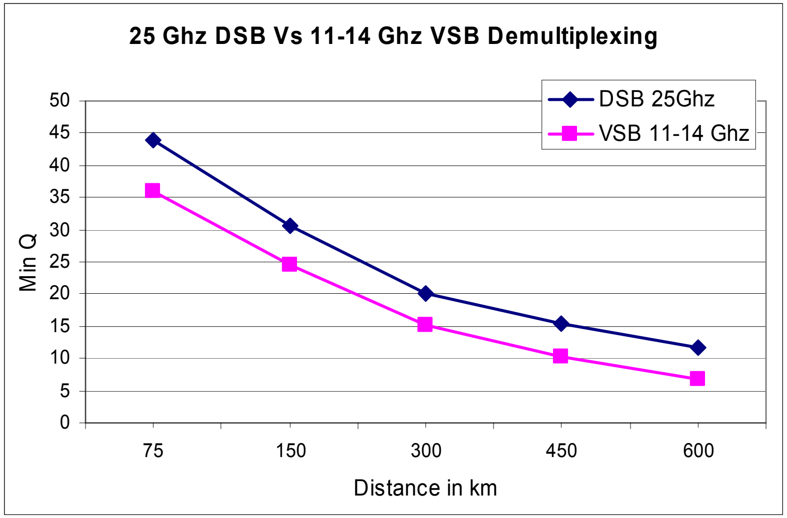
- Performance comparison of uniform polarization and polarization interleave multiplexing

  (channel launch power used: 1.5 mW)



10 Gbit/s WDM system with 0.8 bit/s/Hz spectral efficiency (contd.)

- Performance comparison of alternating 11-14 GHz spaced VSB demultiplexed system with a 25 GHz spaced DSB system
  - Performance of DSB system does not improve significantly with polarization interleave multiplexing
  - Maximum distance reached with a minimum BER of 10^{-12} by
    - 0.4 bit/s/Hz DSB system is 900 km
    - 0.8 bit/s/Hz VSB demultiplexed system is 600 km



Channel launch power used is 1.5 mW

Conclusions

- A reported experimental 40 Gbit/s VSB demultiplexing WDM system with a spectral efficiency of 0.64 bit/s/Hz was successfully modeled using FiberSim.

- An effective Raman amplifier equivalent model was developed which helped to decrease the simulation time considerably, without loss of accuracy.

- Analysis on various simulation parameters showed the following are significant in a high capacity spectrally efficient WDM system
  - Polarization interleave multiplexing
  - Dispersion slope compensation and residual dispersion per span
  - Mitigation of SRS through different EDFA gains in the C-band and L-band

- A 10 Gbit/s VSB demultiplexing WDM system with 0.8 bit/s/Hz spectral efficiency was designed. The design parameters obtained are
  - Optimal channel spacing scheme: Alternating 11-14 GHz channel spacing
  - Optimal Demultiplexer parameters: 12 GHz optical BW with 1 GHz offset frequency
  - Optimal channel launch power: 1.761 dBm (i.e. 1.5 mW)

Future work

- WDM systems with VSB-RZ signaling at the transmitter can be designed and compared with VSB demultiplexing technique
- 10 Gbit/s WDM system reported can be redesigned to increase the transmission distance by compromising a bit on the spectral efficiency. (i.e. 15 GHz average spacing scheme can be used)
- Use of other modulation formats like carrier-suppressed RZ in increasing spectral efficiency can also be investigated

Thank You!

Vestigial Side Band Demultiplexing for High Spectral Efficiency WDM systems

By

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14 January 2004

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