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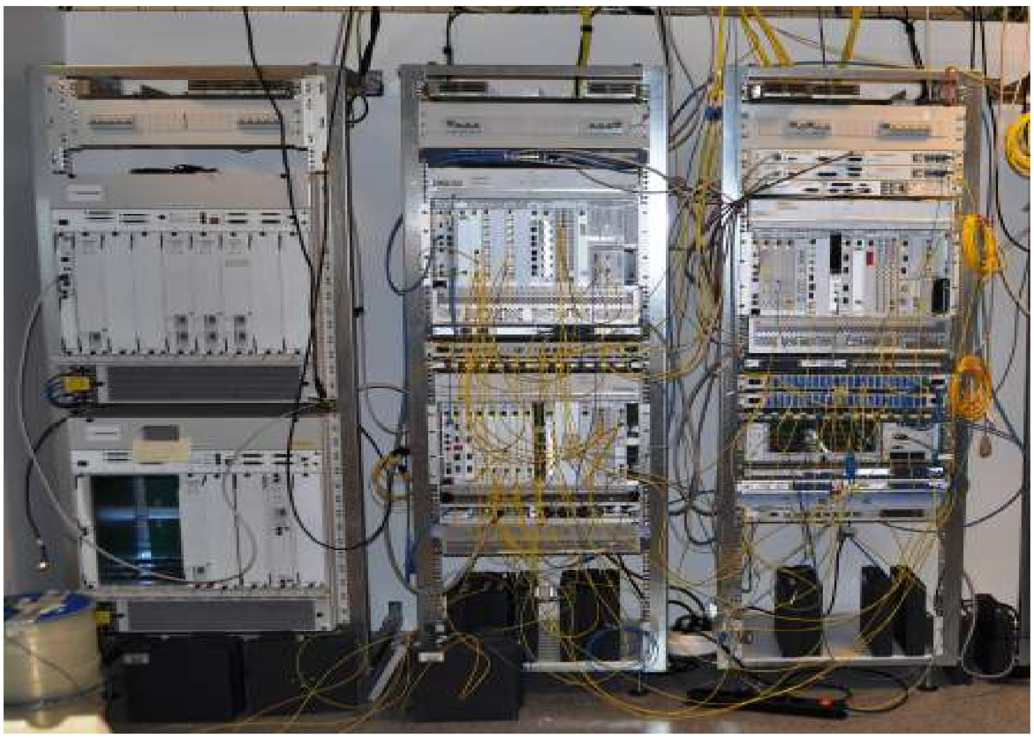

Verification of Equipment Compatibility for 10G/40G/100G Systems

Master of Science Thesis in the Master Degree Programme, Photonics Engineering

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Executive summary and conclusion

Telecommunication service provider companies need to keep track of the fast growing demands of their customers and have to adopt themselves to the new trends and technologies in order to be able to compete in the market.

High bitrates have the advantage of using the bandwidth more efficiently and having an increased capacity which is a key factor for bandwidth-demanding services like Video-On-Demand, Mobile Internet and Broadcast TV. To meet these demands, service providers are upgrading to more promising higher bitrates. However, service providers have widely invested large amounts of money in legacy bit rate of 10 Gbps and it would be too costly for them to have a new infrastructure for higher bitrates while they technically lose what they have spent in the legacy bit rate. Therefore, it is much more affordable for them to use current structure to transport higher bit rates.

This report investigates the possibilities and probable penalties associated with using 10 Gbps systems for propagating 40 Gbps and 100 Gbps signal along with the legacy 10 Gbps signals in the system and studies their co-existence conditions and imposed limitations.

Throughout this report, compatibility of various equipments and methods currently used for 10 Gbps systems has been studied. Drawbacks that worth an extra attention have been pointed out and finally some suggestions for the optimized performance of studied equipments and methods have been presented.

Organization in this report is as the following:

The first chapter discusses the fundamental knowledge and definitions about DWDM networks. Second chapter gives a detailed view about the most important parameters of 10 Gbps systems and continues with reviewing what changes these parameter would have in 40 Gbps DPSK and 100 Gbps DP-QPSK systems. It finished with a brief look at what makes the upgrade urgent and how critical and cost-bearing are the coexistence scenarios. The third chapter begins with the equipments that have been tested and touches upon their manufacturing technique and implementation and later on presents the details of the tests performed and the achieved results. It is concluded by suggesting a number of guidelines to improve and facilitate the compatibility and coexistence of 40 Gbps and 100 Gbps signals in 10 Gbps systems. A list of references is provided at the end of the report.

Key words: DWDM, 10 Gbps OOK, 40 Gbps DPSK, 100 Gbps DP-QPSK

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Table of Contents

1 Background 1
1.1 A short description of WDM networks 1
1.1.1 What is WDM? 1
1.1.2 WDM network hierarchy 1
1.1.3 Different WDM channel patterns 2
2 Modulation formats under study 4
2.1 10 Gbps OOK technology 4
2.1.1 Modulation format 4
2.1.2 Data rate 5
2.1.3 Dispersion 6
2.1.4 Non-linear effects 7
2.1.5 OSNR 8
2.1.6 Cost and complexity 8
2.2 40 Gbps DPSK technology 9
2.2.1 Modulation format 9
2.2.2 Bit rate and FEC 10
2.2.3 Dispersion 11
2.2.4 Non-linear effects 12
2.2.5 OSNR 13
2.2.6 Cost and complexity 13
2.3 100 Gbps DP-QPSK technology 13
2.3.1 Modulation format 13
2.3.2 Dispersion 14
2.3.3 Non-linear effects 15
2.3.4 OSNR 15
2.3.5 DSP 15
2.3.6 Cost and complexity 16
2.4 40/100 Gbps migration necessity 17
2.4.1 A comparison with 10 Gbps system 17
2.4.2 Compatibility and co-existence 18
3 Details of migration scenario 18
3.1 Equipment 18
3.1.1 Transceivers 18
3.1.2 Filters 19
3.1.3 Amplifiers 20
3.1.4 Wavelength Selective Switch (WSS) 21
3.1.5 Optical Channel Monitor (OCM) 22
3.1.6 Dispersion Compensating Module (DCM) 25
3.1.7 Tunable Dispersion Compensator (TDC) 25
3.2 Experimental results 27
3.2.1 BER versus OSNR for 40 G and 100 G 27
3.2.2 The effects of filtering on 40 Gbps and 100 Gbps signals 35
3.2.3 The effects of filtering on BER versus OSNR 37
3.2.4 OCM performance 40
3.2.5 TDC performance 52

3.3 Guidelines for upgrade 55
3.3.1 BER versus OSNR for 40 G and 100 G 55
3.3.2 The effects of filtering on 40 Gbps and 100 Gbps signals 56
3.3.3 The effects of filtering on BER versus OSNR 56
3.3.4 OCM performance 56
3.3.5 TDC performance..... 57
3.4 Future works..... 57
4 References 58
5 Appendices 61
5.1 Appendix 1: Data sheets 61
5.1.1 XFP 61
5.1.2 300-pin transceiver..... 62
5.2 Multiplexer/Demultilexer 62
5.3 Wavelength blocker..... 64
5.4 Optical Interleaver Unit (OIU) 65
5.5 Optical Amplifier (EDFA) 66
5.6 Dispersion Compensating Module 67
5.7 40 Gbps DPSK module..... 67
5.8 100 Gbps DP-QPSK module..... 70

Table of Figures

Figure 1-1: A noticeable jump in traffic capacity in mid-90s 1
Figure 1-2: Separation criteria between the long haul and metropolitan area networks2
Figure 1-3: CWDM and DWDM wavelength grid based on ITU-T rec. G.694.2 3
Figure 2-1: NRZ-OOK signal format..... 4
Figure 2-2: RZ-OOK signal format 5
Figure 2-3: Distorted signal caused by PMD 6
Figure 2-4: Non-linear impairments in a WDM system 9
Figure 2-5: Signal constellation of binary on-off keying (left), and binary phase shift keying (right)..... 10
Figure 2-6: The three parts of OTN format (G.709) in which FEC is separated from data 11
Figure 2-7: Advantages of OTN format 11
Figure 2-8: DP-QPSK Transmitter block diagram..... 14
Figure 2-9: DP-QPSK Receiver block diagram..... 14
Figure 2-10: Schematic of the DSP blocks in a digital coherent receiver 16
Figure 3-1: Wavelength blocker block diagram..... 20
Figure 3-2: Building block for the interconnection of Mux/Demux and OIU..... 20
Figure 3-3: Changing polarization of incoming light by applying a voltage to LC cell 21
Figure 3-4: Signal switching based on polarization state..... 21
Figure 3-5: Binary switching configuration 22
Figure 3-6: (a) Separation of different colors in a DWDM signal using VPG (b) their power spectrum..... 22
Figure 3-7: Functional schematic of company G's OCM module [after OCM spec]..... 23
Figure 3-8: a) MEMS tunable filter schematic b) 4x1 switch 24
Figure 3-9: Schematic of OCM module 24

Figure 3-10: Group Delay Response for individual etalons (up) and cascaded etalons (middle) and different slopes resulted from different distribution of GDR curves 26
Figure 3-11: Test setup 28
Figure 3-12: 50 GHz spaced A (10G) – B(40G) – C(10G) and OSNR penalties for each power level 29
Figure 3-13: 100 GHz spaced A (10G) – B(40G) – C(10G) and OSNR penalties for each power level 30
Figure 3-14: 200 GHz spaced A (10G) – B(40G) – C(10G) and OSNR penalties for each power level 30
Figure 3-15: 50 GHz spaced A (10G) – B(100G) – C(10G) and OSNR penalties for each power level 31
Figure 3-16: 100 GHz spaced A (10G) – B(100G) – C(10G) and OSNR penalties for each power level 32
Figure 3-17: 200 GHz spaced A (10G) – B(100G) – C(10G) and OSNR penalties for each power level 33
Figure 3-18: 50 GHz spaced A (40G) – B(100G) – C(40G) and OSNR penalties for each power level 34
Figure 3-19: 100 GHz spaced A (40G) – B(100G) – C(40G) and OSNR penalties for each power level 34
Figure 3-20: 200 GHz spaced A (40G) – B(100G) – C(40G) and OSNR penalties for each power level 35
Figure 3-21: Filtering effect measurement setup 35
Figure 3-22: Unfiltered 40 G and 100 G signal spectrum 36
Figure 3-23: Filtering effect of different components on 40 G signal 37
Figure 3-24: Filtering effect of different components on 100 G signal 37
Figure 3-25: Filter profile 38
Figure 3-26: Filter profile from 50 GHz to 20 GHz 38
Figure 3-27: BER vs. OSNR for filtered 40 G signal 39
Figure 3-28: BER vs. OSNR for filtered 100 G signal 39
Figure 3-29: BER penalty for decreasing BW from 46 GHz to 30 GHz 40
Figure 3-30: Test setup for company G OCM 40
Figure 3-31: Power difference between OCM and calibrated power meter for 10G and 40G signals 41
Figure 3-32: Adjacent channels' power effect on center channel for 10G and 40G...... 42
Figure 3-33: 10G signal, OCM detected power vs. calibrated power meter for different conditions 42
Figure 3-34: 10G signal, difference with calibrated power meter for different conditions 43
Figure 3-35: 40G signal, OCM detected power vs. calibrated power meter for different conditions 43
Figure 3-36: 40G signal, difference with calibrated power meter for different conditions 44
Figure 3-37: 40G signal, difference with calibrated power meter for different conditions 44
Figure 3-38: 100G signal, difference with calibrated power meter for different conditions 44
Figure 3-39: Minimum detectable power levels 45
Figure 3-40: Adjacent channel power effect for 10G, 40G and 100 G 46

Figure 3-41: 10G signal, OCM detected power vs. calibrated power meter for different conditions 47
Figure 3-42: 10G signal, difference with calibrated power meter for different conditions 47
Figure 3-43: 40G signal, OCM detected power vs. calibrated power meter for different conditions 48
Figure 3-44: 40G signal, difference with calibrated power meter for different conditions 48
Figure 3-45: 100G signal, OCM detected power vs. calibrated power meter for different conditions 49
Figure 3-46: 100G signal, difference with calibrated power meter for different conditions 49
Figure 3-47: Minimum detectable power for 10G, 40G and 100G compared with a calibrated power meter 50
Figure 3-48: Adjacent channel power effect for 10G, 40G and 100 G 51
Figure 3-49: Measurement setup for company K's TDC 52
Figure 3-50: OSNR vs. dispersion value for weak and strong filtration at -5° C........ 53
Figure 3-51: OSNR vs. dispersion value for weak and strong filtration at 23° C........ 53
Figure 3-52: OSNR vs. dispersion value for weak and strong filtration at 70°C........ 53
Figure 3-53: Operating bandwidth for different dispersion settings at 10 ps Group Delay Ripple 54

Table of Tables

Table 1: Bit rate increased caused by adding FEC [7] 5
Table 2: Power levels (dBm) for center channel measured by the company H's OCM and power meter and its neighbors 46
Table 3: Power levels (dBm) for center channel measured by the company I's OCM and power meter and its neighbors 51

1 Background

1.1 A short description of WDM networks

1.1.1 What is WDM?

Wavelength **D**ivision **M**ultiplexing (WDM) is a method of multiplexing optical signals by aggregating different *wavelengths* (colors) in a single optical fiber. By choosing different wavelengths, this single span of optical fiber can be a “bidirectional” link (i.e. Uplink and Downlink).In a DWDM network, these wavelengths shall be chosen from a certain bandwidth range (ITU-T’s C and L band).

In the mid-90s, WDM technology, with help of a new kind of fiber amplifier called EDFA (Erbium Doped Fiber Amplifier), could dramatically increase the data traffic capacity (as shown in figure 1-1) by almost two orders of magnitude and this was the beginning of a new era in optical fiber communication.

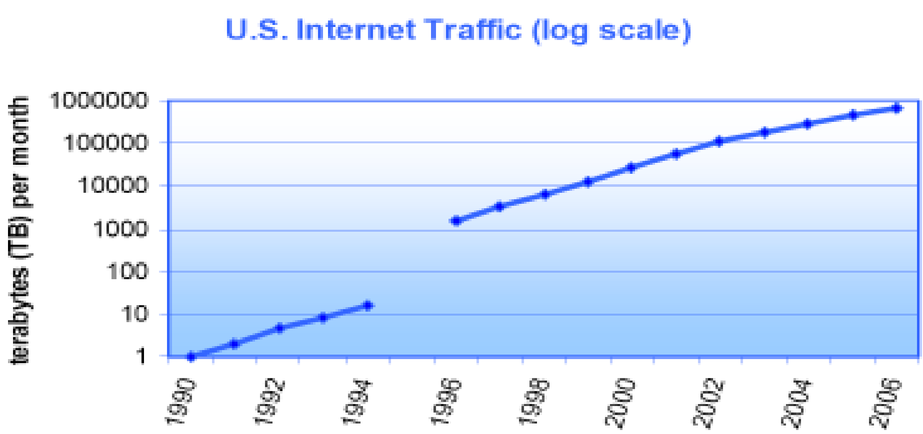


Figure 1-1: A noticeable jump in traffic capacity in mid-90s
[After B.Swanson and G.Gildez, Jan 2008]

1.1.2 WDM network hierarchy

Based on the coverage distance, DWDM networks are divided into three major categories:

- Long Haul Networks
- Metropolitan Area Networks (core & regional)
- WDM Access

Long haul reach, as the naming suggests, is ranging thousand kilometers and beyond which is optimized for maximum performance that makes it a good choice to interconnect cities or different regions.

Metropolitan Area networks or in short Metro networks along with Regional Networks (as shown in figure 1-2) have the role of interconnecting central offices together or to the next sub layer called Access Network. Access Network is a median between central offices that directly feed the end users such as business or residential or service providers or etc. Access network reach could be in order of few tens of kilometers and has the role of interconnecting customers' traffic to carrier side which is located at central office (CO). Metro network has a broader reach than access network; it connects a number of COs with each other within a region. Having length of few hundred of kilometers to a thousand kilometer, metro network acts as the interface between access network and long haul network or in other words, connecting "end-user costumers" to the global networks.

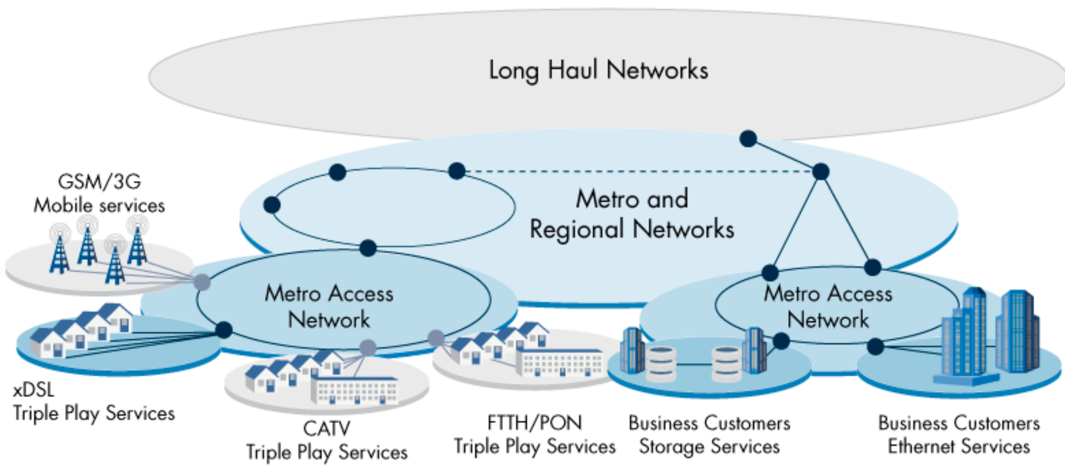


Figure 1-2: Separation criteria between the long haul and metropolitan area networks
[Transmode, 2009]

1.1.3 Different WDM channel patterns

WDM system is basically categorized into two different wavelength patterns:

- Coarse WDM (CWDM)
- Dense WDM (DWDM)

CWDM mainly focuses on the short range networks (metro and access) while DWDM, by using amplifiers, can accommodate almost all three ranges that has been defined earlier.

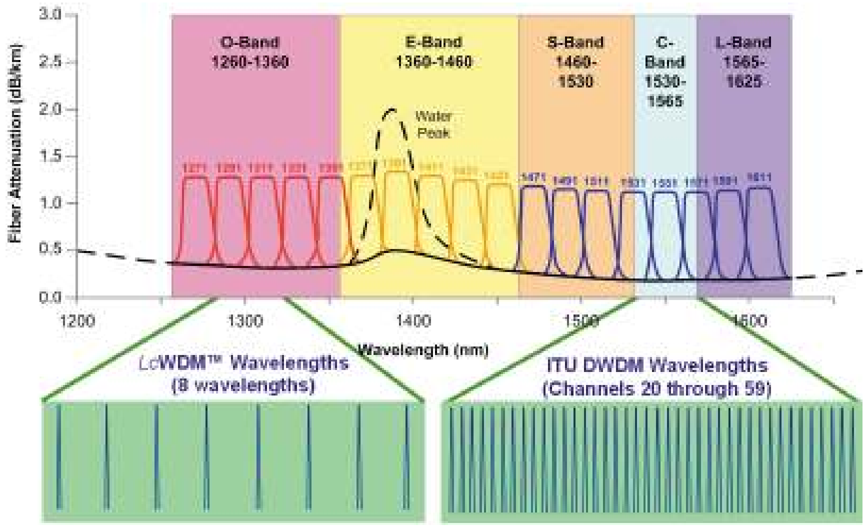


Figure 1-3: CWDM and DWDM wavelength grid based on ITU-T rec. G.694.2
[http://www.cable360.net/ct/strategy/businesscases/30007.html

On the other hand, as shown in figure 1-3, DWDM systems have many channels (Typically channel spacing could be 200, 100, 50 and 25 GHz) aggregated in a smaller bandwidth called the C band .C Band is defined as frequency range between 191.9 THz up till 195.8 THz for even channels (100 GHz spacing) and 191.85 THz up till 195.75 THz for odd channels (50 GHz spacing) .This strict limitation requires precise and stable lasers accompanied by narrow-band filtering and could support amplification and regeneration in order to increase the reach up to thousands of kilometers.

2 Modulation formats under study

2.1 10 Gbps OOK technology

Currently, 10 Gbps is today's commodity technology for high capacity fiber optic networks. It seems to be highly efficient in many aspects; most of service providers have made a large amount of investment in buying system equipments working in 10 Gbps.

Like the previous lower bit rate formats, 10 Gbps has its own set of characteristics as they are discussed in the coming subchapters.

2.1.1 Modulation format

One of the modulation formats that are widely used in 10Gbps systems is On-Off Keying (OOK) which itself is the simplest form of a more general modulation scheme called Amplitude Shift Keying (ASK). The most important advantages of this format are its low cost implementation and a simple modulator design which makes it the modulation format of choice for commercial 10 Gbps transmission [1, 2, 3]. To generate electrical binary bits in this format, as shown in figure 2-1, laser light shall be simply turned on (for "1" bit) and off (for "0" bit).

OOK is considered to appear in two different digital data formats:

- Non-Return to Zero (NRZ-OOK): In this format, voltage levels are high ("1") or low ("0") for the entire bit duration.

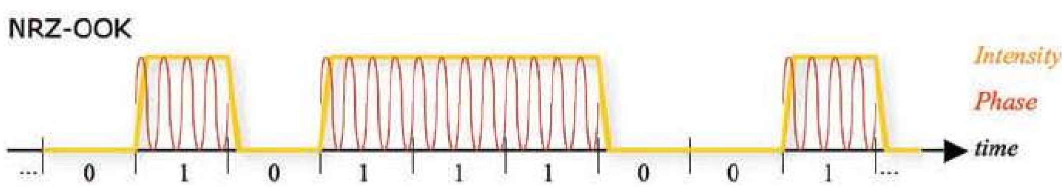


Figure 2-1: NRZ-OOK signal format
[1]

- Return to Zero (RZ-OOK): High voltage level ("1") in this method is basically shorter than the bit duration and does not occupy the entire bit slot as shown in figure 2-2. Depending on the type of RZ it can have 33%, 50 % or 67 % duty cycle which means voltage is high in those portions of bit duration. To implement a RZ, a NRZ modulator could be used followed by a pulse carver which practically filters out the bit slot according to the targeted duty cycle [2, 3].

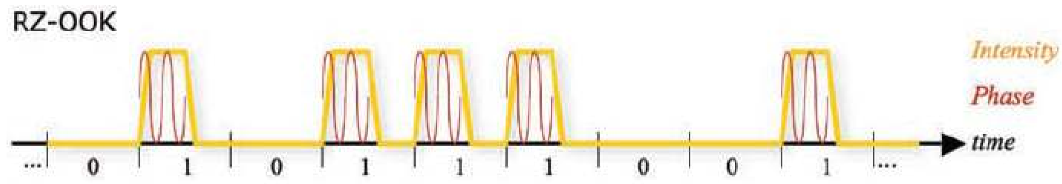


Figure 2-2: RZ-OOK signal format
[1]

Beside the low cost and simplicity, the advantage of NRZ-OOK is its small bandwidth which makes it so promising in the transmission schemes where bandwidth is a limitation. On the other hand, RZ is more tolerant toward pulse broadening and intrinsically has the clock recovery but has the disadvantage of less energy per symbol and higher frequency [1, 2, 3, 4].

2.1.2 Data rate

Probably the most important terminology in a transmission format is bit rate. The Bit rate is defined with the speed in which the data is being transmitted through the line and is quantified with the number of bits sent/received per second (bps). Since year 2000 and onward, bit rate of most operational systems are presented in order of Mega bps and Giga bps or even higher. In order to have a standardized bit rates which could be internationally accepted ITU-T and IEEE have introduced a series of standards to represent a logical hierarchy of data rates. Examples of these standards are SDH/SONET and Ethernet. In this sub chapter we mainly focus on 10 Gbps which could be translated into any of the mentioned standards in fixed but different bit rate values which would be describe as the following:

- SDH / SONET: Synchronous Digital Hierarchy / Synchronous Optical NETworking's10Gbps is considered to be the STM-64/OC-192 generation with the fixed data rate of 9.953280 Gbps[5].
- Ethernet: R-series interfaces (R, LR, SR and ER) of 10GbE (also known as LAN PHY) have all the same fixed data rate of 10.3125 Gbps[6].

These standards are further enhanced (in term of errors) by introducing a technique that adds extra bits to data streams using a code. At the receiver side these added bits would be used to correct the errors occurred during transmission in the fiber length. This technique is called Forward Error Correction (FEC) .The FEC scheme used in ITU-T recommendation G.709 used Reed-Solomon coding (RS(255,239)) which means over-head bits are 6.27 % more[7]. Table 1 discusses the change in bit rate of SDH/SONET and Ethernet with added over-head:

Client Signal Type	**Client Signal**	**OTN Line Signal (G.709)**	**Bit Rate before FEC (Gbps)**	**Bit Rate after FEC (Gbps)**
SDH/SONET	STM-64/OC-192	OTU2	9.953	10.709
Ethernet/Fiber Channel	10GbASE-R/FC10G	OTU2e	10.3125	11.095

Table 1: Bit rate increased caused by adding FEC **[7]**

2.1.3 Dispersion

Dispersion is a considerable impairment in optical fiber communication. It could be seen as the difference in phase velocity of light when traveling inside a fiber. There are two important types of dispersion affiliated with fiber optics:

- Chromatic Dispersion (CD): As the name suggests, is referred to as the delay in arrival time at the destination for optical signals with different wavelengths (colors of light) traveling through fiber. Refractive index is wavelength-dependant so this is the main reason behind the timing delay. This delay time is directly related to the wavelength of light meaning that optical signals having shorter wavelengths arrive at a different time at the destination than the ones having longer wavelength this phenomenon causes broadening of optical pulses distorting the original pulse shape. When the bit rate of the signal is relatively high, each individual pulse would be shorter and positioned closer to the neighboring pulse. By introducing chromatic dispersion after some length of fiber, pulses become broader and interfere with each other.10 Gbps signals suffer more from the distorting effects of dispersion which can limit the reach. Different modulation formats have different resilience toward the CD; for instance, Ethernet has lower CD limits (ps/nm.km) than SDH/SONET at the same data rate [8].
- Polarization Mode Dispersion (PMD): This type of dispersion is caused by the birefringence in the fiber meaning that the refractive index of the fiber is different for orthogonal polarization components causing each polarization component to travel with different speed and creates a timing delay between two components at the destination as shown in figure 2-3. PMD can be quantified by Differential Group Delay (DGD) measured in picoseconds. It is considered to be the timing difference introduced between the two polarization modes and can be observed at the receiver side of the link. For a 10 Gbps system, the maximum allowable PMD value is considered to be approximately 5 ps [8].

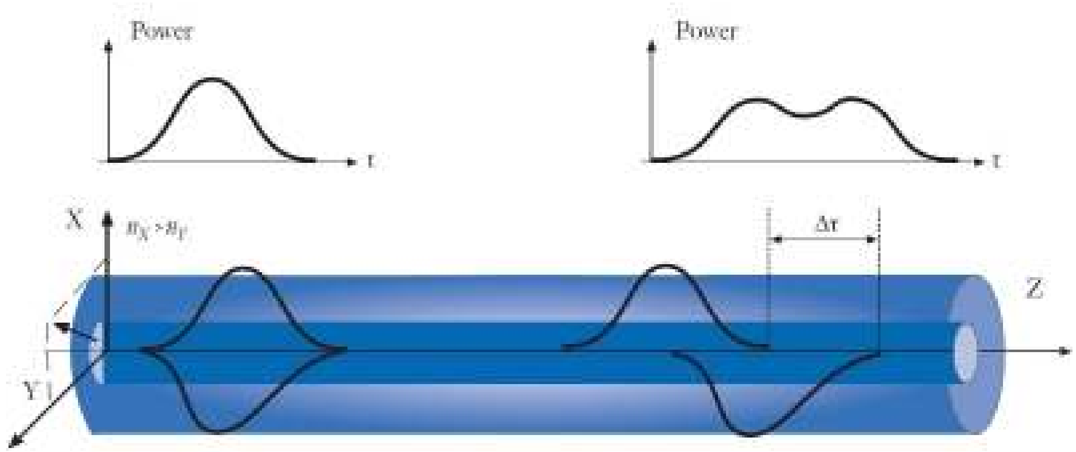


Figure 2-3: Distorted signal caused by PMD
[9]

There is an important and widely used common term affiliated with optical communication called “dispersion penalty” which is defined as the differences in received power levels in two situations i) Having no length of optical fiber in the link called back-to-back communication and ii) having a certain length of optical fiber called over-the-fiber communication. The difference in power level is basically contributed by the dispersion introduced in (ii) situation distorting the signal.

Mentioned power difference shall be compensated to maintain the back-to-back received signal quality. Dispersion tolerance is defined as the maximum and minimum dispersion we can accept in a system while having a certain amount of dispersion penalty.

2.1.4 Non-linear effects

Non-Linear Effects (NLE) refer to a phenomenon that relates the intensity of light inserted to the fiber with a change in refractive index. Also, inelastic scattering phenomena can be a trigger to the non-linear effects [10]. Change in refractive index according to the intensity of input signal is called the Kerr Effect.

Based on the type of the input signal, Kerr Effect generated nonlinearities in fiber can be divided into 3 categories:

- Four Wave Mixing (FWM): type of a fiber non-linearity that is generated by the interference between 3 different channels (λ's) interacting with each other and producing unwanted fourth channel. It is often a sum-and-subtraction phenomena happening between 3 different signals wavelengths which their sum or subtraction of two of them with the third one produces a new component interfering with one of the main components. Chromatic Dispersion, by introducing a delay relative to wavelength to each channel component, can help reduce the unwanted effects of FWM. Also, by arranging irregular channel spacing (Due to channelized nature, this is not a good solution for DWM networks); FWM can be reduced to some extent.
- Self Phase Modulation (SPM): it could be seen as an effect which a signal has on itself and the resulting signal becomes wider than the original. When light intensity increases, it will change refractive index of the fiber modulating the phase of the signal in those spots causing a spread in the wavelength spectrum. The resulting spread is a shift toward shorter wavelengths at the trailing edge (blue shift) and a shift toward longer wavelengths at the leading edge (red shift) of the signal. This phenomenon acts as an exact opposite to effect of a positive Chromatic Dispersion in fiber.
- Cross Phase Modulation (XPM): The effect which a signal in one channel has on the phase of another signal in another channel is XPM. The unwanted effect is (due to the Kerr effect) to broaden the signal.

Beside the Kerr effect on the signal, there are two other unwanted phenomena categorized under scatterings. They are based on the scattering of laser signal by fiber molecular vibrations or by induced virtual gratings. When a photon converts to a lower energy photon and the energy difference will be in form of a phonon. Depending on the type of produced phonon (optical or acoustic), Raman and Brillouin scatterings would rise respectively [4].

- Stimulated Raman Scattering (SRS): Transfer of power of a signal at shorter wavelengths to signals at longer wavelengths. Photons of the laser light are absorbed by the fiber molecules and are re-emitted. This process changes the wavelength of light and shifts it to lower or higher frequencies. The shift is proportional to the amount of energy being converted to phonon. Wavelength difference (shift) is around 100 nm [8].
- Stimulated Brillouin Scattering (SBS): is a scattering phenomenon in which backscattered light in fiber causes loss of power. When inserting high powers to the fiber, refractive index of fiber changes periodically acting like a grating. The grating-like media would scatter the incoming optical signal in backward direction.

2.1.5 OSNR

It is the ratio between signal powers at its peak value to the noise power ground measured at (virtually) the same point as the peak. OSNR is one of the most important parameters in WDM networks' design and it is much influenced by different factors such as attenuation and dispersion (CD and PMD) in the fiber. OSNR is related to Bit Error Rate (BER) which is a measure of number of bits that have been identified as errors in the transmission. To increase the performance and improve OSNR value, amplifiers should be used but it should be kept in mind that by using amplifiers, not only the signal is amplified but noise which is passing through the same path as the signal will be amplified too. In addition, amplifier itself will contribute noise to the system.

2.1.6 Cost and complexity

10 Gbps system has an elevated level of complexity in comparison with its predecessor bitrates in different domains:

The level of complexity in 10 Gbps systems is varied. The modulation format (NRZ-OOK) is relatively simple method of modulation since the only requirement is to detect a signal power (exceeding than a threshold) for "1"s and receiving no light (below a threshold) for "0"s. Therefore modulator / Demodulator implementation is technologically not so difficult. Spectral efficiency is 0.2 bits/ Hz in a 50 GHz grid system [11].

A bit rate of 10 Gbps imposes rather tight conditions to many raised impairments in optical fiber communication. It has a stronger effects in provoking dispersion related impairments (CD and PMD) and non-linear effects such as FWM, SPM and XPM.

In a long haul / Metro WDM network, with a conventional SMF (CD coefficient of 17 ps/nm.Km [12]), pulse spreading can be problematic but at the same time, CD is a counter-measure to non-linear impairment.

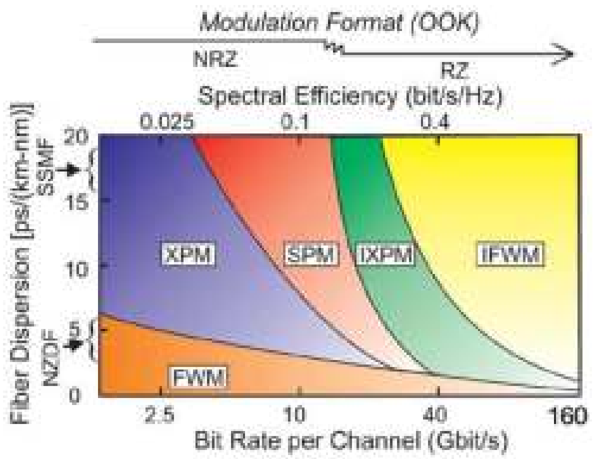


Figure 2-4: Non-linear impairments in a WDM system
[13]

It has been demonstrated [14] that dispersion management can decrease the destructive effect of FWM, SPM and XPM in an OOK-modulated 10 Gbps system but still there is a need for CD compensator (Dispersion Compensator Fiber (DCF) or Dispersion Compensation Module (DCM) life Fiber Bragg Gratings (FBG)…).Figure 2-4 illustrates the most important impairments by increasing the bit rate. For a 10 Gbps OOK signal, the dominant nonlinear impairment at the Standard Single Mode Fiber is SPM while for example it is IXPM for 40 Gbps and IFWM for 100 Gbps signals.

PMD could (in a limited extend at 10 Gbps) be an issue to proper signal detection therefore a PMD compensator should be provided to decrease the unwanted effect.

2.2 40 Gbps DPSK technology

2.2.1 Modulation format

Differential Phase Shift Keying (DPSK) is one of the modulation formats of choice for 40 Gbps. There are a number of different other formats but DPSK could be considered as the most cost effective one. It encodes information on the binary phase change between two consecutive bits where it encodes “1” into π phase shift and no phase change for “0” bits.

It appears (like OOK format) in two digital data formats of RZ and NRZ with/without implementing a pulse carver respectively.

The most important advantage of DPSK to OOK would be a 3-dB better receiver sensitivity for fixed average optical power which is gained by a √2 more symbol spacing in constellation diagram shown in figure 2-5.

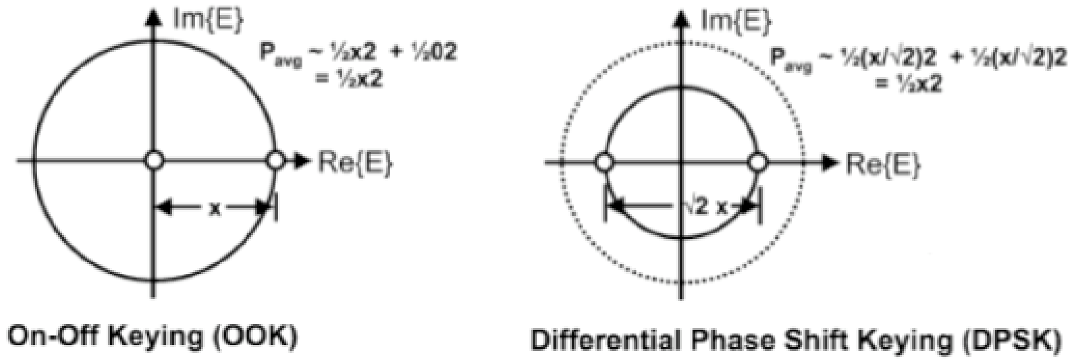
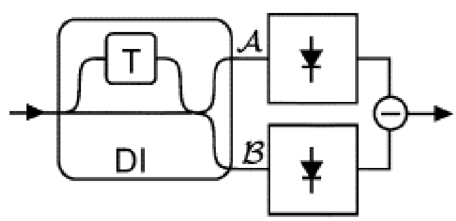


Figure 2-5: Signal constellation of binary on-off keying (left), and binary phase shift keying (right)
[http://code.ua.pt/attachments/1476/Imagem_4.png]

Since exact phase modulation is vital for DPSK, therefore transmitters are most conveniently implemented using Mach Zehnder Modulator as phase modulator so that an exact π phase jump would be produced.

On the receiver side, transmitted signal by a DPSK module cannot be directly received without any further implementation since signal becomes more complex by phase modulation. However, delay-and-add Mach-Zehnder Interferometer (MZI) is required to decode the DPSK signal [11]. It is inserted in the optical path of the receiver in order to convert differential phase modulated signals into intensity modulated ones in which the demodulation process is much easier. MZI block would split the phase modulated signal into two paths, from which they will experience a delay difference equal to the bit duration T (25 ps at 40 Gbps) in order to let two neighboring bits interfere at the output and by comparing the delayed version with the original version, π or 0 phase difference could be translated to "1"s and "0"s [11, 13].



Balanced DPSK receiver with an optical Delay Line
[13]

2.2.2 Bit rate and FEC

Like 10 Gbps, 40 Gbps comes in different data rate formats like SONET/SDH, Ethernet and Optical Transmission Network (OTN) which is a combination of SONET/SDH with bandwidth expansion capabilities offered by DWDM [33]. OTN defines a standard bit rate of 43,02 Gbps (using Reed-Solomon (RS) code to realize Forward Error Correction. RS coding is chosen because of its low complexity, relatively high error correction capabilities and low burst sensitivity) [33].OTU-3 has RS (255/236) coding scheme times SDH/SONET data rate of 39,81 Gbps resulting in 43,02 Gbps [34]). OTU-3e2 is over clocked (increasing clock tolerance of ±100 ppm instead of standard OUT's clock tolerance of ±20 ppm to better control the jitter) bit rate format of OUT-3 composed of 4 x OTU-2e (4 x 11,09 ≈ 44,58 Gbps) which OTU-2e itself is designed to transmit 10 GbE LAN PHY. This is specified in G.Sup43.In figure 2-6, three important parts of an OTN signal that are overhead, Payload (data) and FEC (correcting part of the stream) are outlined. In figure 2-7, the advantages of OTN (that are a combination of advantages of SDH/SONET together with that of Fiber Channel and Gigabit Ethernet) are discussed.

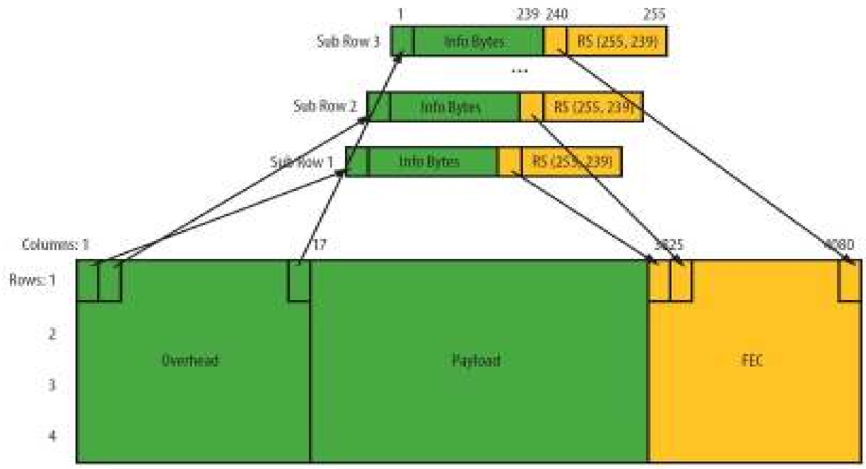


Figure 2-6: The three parts of OTN format (G.709) in which FEC is separated from data [15]

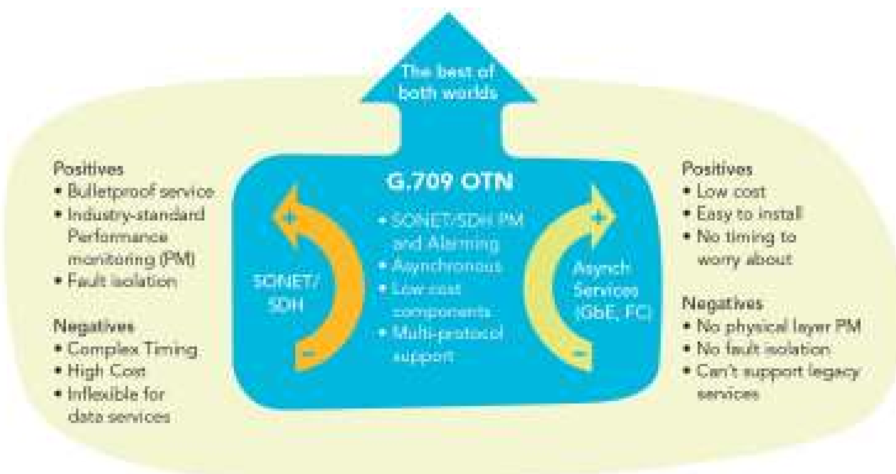


Figure 2-7: Advantages of OTN format
[The Value of OTN for Network Convergence and IP/Ethernet Migration]

2.2.3 Dispersion

As in 10 Gbps, the most important dispersion forms are chromatic dispersion and polarization mode dispersion. Both of them are investigated according to the dispersion referenced on 10 Gbps defined in 2.1.3.

- **Chromatic Dispersion**: In a 40 Gbps system, dispersion shall be tightly controlled since the signal is more prone to degradation caused by dispersion. 40 Gbps signal is almost 16 times more sensitive to dispersion effects than 10 Gbps signal due to factors such as having a 4-times wider spectrum which results in more severe pulse broadening and 4-times smaller bit period, making the signal more sensitive to inter-symbol-interference (ISI) [16]. Having said this, it seems that precisely controlling dispersion in 40 Gbps systems is mandatory in order to have a distortion-free transmission. To compensate for static CD, there are two technologies available, Fiber Bragg Grating (FBG) and Dispersion Compensator Fibers (DCF) and for tunable DC, Gire-Tournois Etalons (discussed in details in 3.1.7) and Fiber Bragg Gratings are used.

- **PMD**: It has a random nature which makes it so difficult to predict and control in a 40 Gbps system. It is originated by many different factors among which are geometrical asymmetries, mechanical stress, temperature changes, and fiber movement [17]. Therefore it is harder to handle than chromatic dispersion.40 Gbps system is very sensitive to the effects of PMD (about 2,5 ps). It is 4x more sensitive than 10 Gbps system (10 ps) therefore PMD is described as one of the main limiting factors in 40 Gbps system. PMD is related to the length of fiber through the equation below:

$$PMD = <\Delta\tau> \ PMD_{Coeff}\sqrt{L}$$

PMD coefficient is a proportionality coefficient with unit of ps/Km½ relating the length of the fiber (L) to PMD value (in ps) of it and <Δt> is the average Differential Group Delay [9]. For 40G DPSK, this imposes a reach limit of a few tens of kilometers. [17]

2.2.4 Non-linear effects

At such high bitrates, isolated pulse transmission does not suffer from nonlinear impairments because of large pulse broadening .On the other hand, interactions between pulses of the same channel are enhanced which sets the limit for nonlinear transmission [18] . On the contrary to 10 Gbps as it is discussed in 2.1.4, a strong pulse overlaps occurs in the case of 40 Gbps transmission due to four times reduced signal period (or 16 times stronger dispersive effect).Thus the main non linear effects are intrachannel four wave mixing and cross phase modulation [19].The limitation caused by these two nonlinear effect take two different forms. The first is the production of timing and amplitude jitter of the “1”s originating from intrachannel XPM and the second is connected to intrachannel FWM and results in significant amplitude fluctuations as well as creation of Ghost Pulses at the center of “0”s which will gain sufficient energy to be detected as “1”s over a number of spans. The first can be greatly reduced by using a “symmetric” dispersion managed link [18, 19].DPSK signal format suffers less from XPM due to equal pulse energy in each bit period but major nonlinearity penalty in 40 Gbps DPSK is IFWM induced nonlinear noise phase due to the dependence of refractive index of the medium on the intensity of the applied electrical field [20].

2.2.5 OSNR

DPSK has a 3-dB better OSNR sensitivity than OOK due to differential detection. Every doubling of bit rate results in a 3-dB decrease in OSNR. So 40 Gbps has a worse OSNR than 10 Gbps by 6-dB. In summary, 40 Gbps DPSK has 3-db worse OSNR than 10 Gbps OOK. [13, 21, 22] .Amplifiers (like Erbium Doped Fiber Amplifier (EDFA)) are essential for amplifying the signal level to increase the OSNR but at the same time, the Amplified Spontaneous Emission (ASE) noise generated by the EDFA degrades OSNR in Also, by using DPSK format, there would be a gain of about 2.5 dB over long distances.

2.2.6 Cost and complexity

40 Gbps DPSK system has an elevated level of complexity in comparison with its predecessor bitrates. It uses a more complex method of modulation/demodulation based on phase variation and therefore detecting phase variation needs a more advanced modulator/demodulator set. [23]

Distortion caused by the both forms of dispersion (CD and PMD) shall be largely eliminated which requires DCMs and DCFs along the link and a Tunable Dispersion Compensator (TDC) module for compensating CD at the receiver side increasing overall cost and complexity of the system.

However, this complex modulation format has the advantage of better resilience toward nonlinearities. It only suffers from IXPM and IFWM but it is reported that the unwanted effect are much lower than they are for 10 Gbps OOK since it has a ~3 dB lower peak power. [19]

2.3 100 Gbps DP-QPSK technology

2.3.1 Modulation format

Dual-Polarization Quadrature Phase Shift Keying with coherent detection seems to be modulation of choice for 100 Gbps long haul transmission. It is a rather complex modulation format coding 4 bits per symbol by utilizing a beam splitter dividing the output signal of a Continuous Wave signal from laser into the two arms of in-phase (I) and quadrature phase (Q) modulators. Then the output of each arm (named X and Y components) are again recombined producing an output that has X and Y polarized components orthogonal to each other and each component is comprised of I and Q signals making four signals denoted as X/I, X/Q, Y/I and Y/Q yielding symbol rate of 32 Gbaud [24, 25] as shown in figure 2-8.

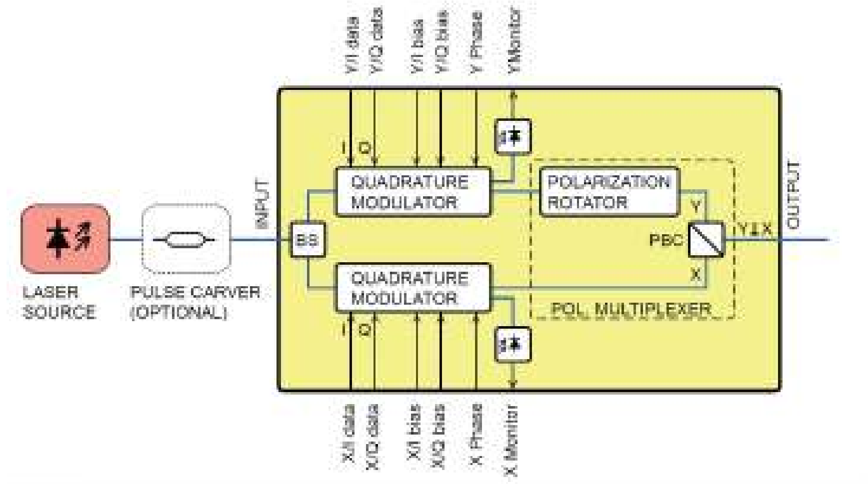


Figure 2-8: DP-QPSK Transmitter block diagram
[26]

At the coherent receiver, received signal is mixed with a tunable laser local oscillator at a frequency close to that of received optical signal which generates mixing products at the difference frequency. Polarization and phase diversity are maintained with help of a beam splitter and optical phase hybrids. The resultant analog signals are then down converted, detected electronically, linearly amplified, digitized in high-speed Analog to Digital Converters and finally passed to Digital Signal Processor Application-Specific Integrated Circuit (ASIC) chip as shown in figure 2-9. DSP ASIC has the important functionality of compensation and equalization for impairments added to the signal along the propagation path through optical fiber such as CD, PMD and non-linear effects distortion.

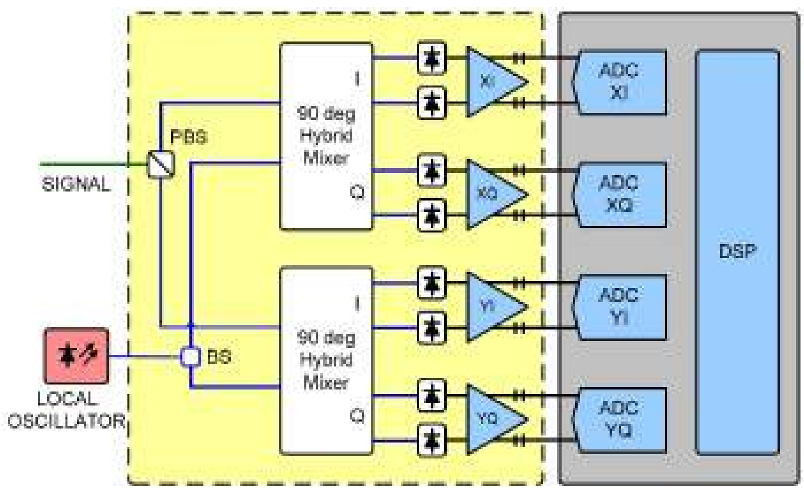


Figure 2-9: DP-QPSK Receiver block diagram
[27]

2.3.2 Dispersion

At 100 Gbps, chromatic dispersion and polarization modulation dispersion are two critical factors for linear signal propagation impairments because they introduce signal distortions penalties that prevent high performance transmission. Their unwanted effects are worsened compared to 10 Gbps and even 40 Gbps. CD tolerance is approximately 100x smaller compared to 10 Gbps and 6.25x smaller than 40 Gbps. Also, DGD tolerance is again 10x smaller comparing to 10 Gbps and 2,5x smaller than 40 Gbps causing the PMD-limited reach become 100x shorter than 10 Gbps and 6.25x shorter than 40 Gbps. But since the optical signal is converted to electrical at the receiver side and is fed to the DSP, all of these distorting impairments are compensated in the electrical domain without any extra cost for physical CD and PMD compensators. Also, at 100 Gbps, there is a DSP at the receiver side, leaving no need for DCFs and DCMs along the link

2.3.3 Non-linear effects

Noise accumulated from amplifiers and nonlinear impairments like SPM and XPM are the only factors that limit the reach. There are no DCF and DCM in the link; therefore intra-channel nonlinearities can be largely reduced since they are produced by those eliminated lumped compensators. The remaining inter-channel nonlinearities such as IXPM between WDM channels (generating timing jitter and nonlinear phase noise) and nonlinear polarization scattering (nonlinear polarization rotation) are considered as the major nonlinear impairments in a 100 Gbps system. [28, 29]

2.3.4 OSNR

The required OSNR for 100 Gbps is 10 dB higher than 10 Gbps and 4 dB higher than 40 Gbps. [30, 32]

DP-QPSK modulation format has 2,5-3 dB better OSNR than direct detection. Also, DSP and FEC (with over head of 20% as compared to 7 % for 10 Gbps and 40 Gbps) can help improve the OSNR with 1,3 dB .The limiting factors are the optical noise added by amplifiers along the link degrading signal to noise ratio. The solution would be to balance the amplifiers' launch power with noise and non-linear effects since increasing input power will increase the nonlinear effects in fiber [32].

2.3.5 DSP

The main advantage of a Digital Signal processing module in a coherent detection 100 Gbps DP-QPSK system is to compensate for the linear signal distortions due to the fiber length like CD and PMD. It simplifies the coherent receiver by moving the complexity of phase and polarization tracking into the digital domain. DSP reconstructs the received signal with help of the blocks detailed in the figure 2-10. [33]

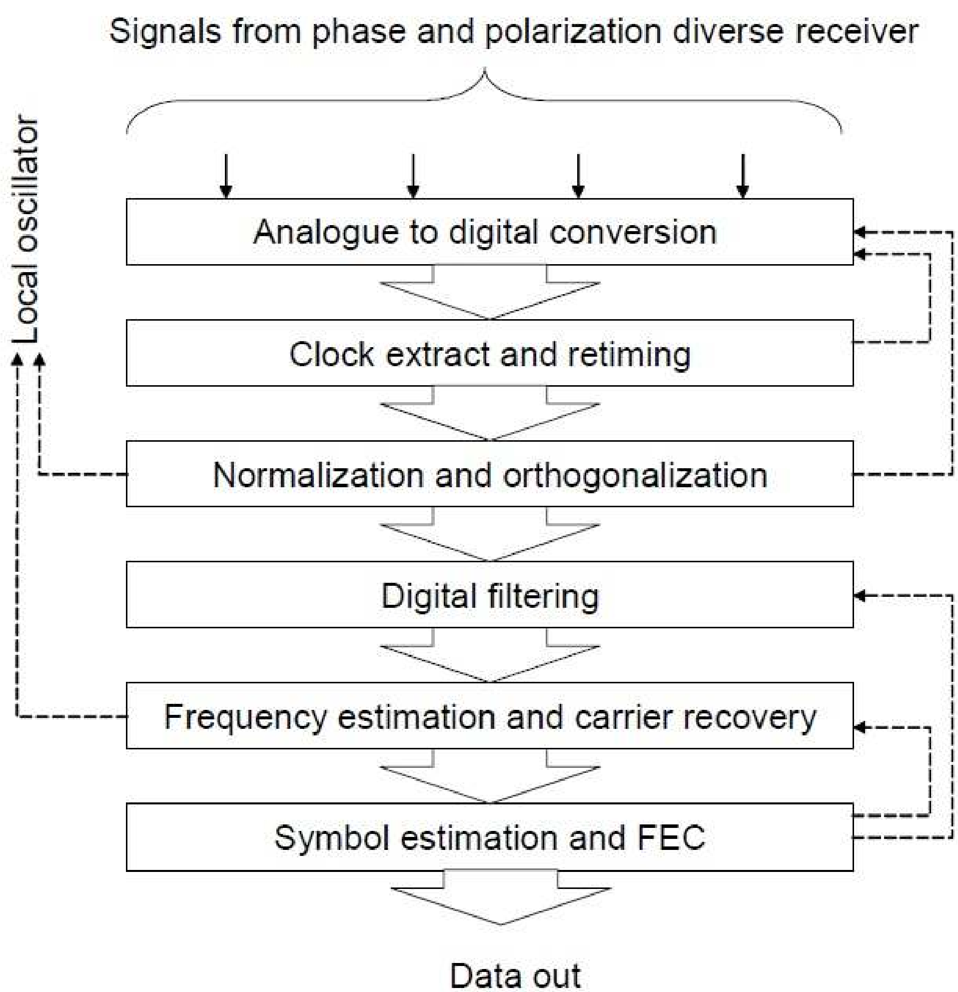


Figure 2-10: Schematic of the DSP blocks in a digital coherent receiver
[34]

2.3.6 Cost and complexity

100 Gbps is a relatively new technology and the key components such as transponders and especially DSP chips are still very expensive. But by further establishment of 100 Gbps systems, its cost would decrease accordingly as in other previous bit rate technologies.

At 100 Gbps, a more sophisticated modulation format is used to minimize the optical impairments effects. DP-QPSK modulator itself is relatively more costly and much more complex than 10 Gbps but having 4 bits of data to be encoded and sent as one optical symbol optical impairments are easier to compensate.

At the receiver side, there are many different stages in a coherent receiver making it complex and costly. DSP and other high speed components have the main share in the high price. But this complexity has a number of advantages as well:

The high speed ADCs and DSP compensate for linear optical impairments that makes administration and control easier. Besides it will eliminate lumped CD compensator along the link and PMD compensator at the receiver. [35]

2.4 40/100 Gbps migration necessity

2.4.1 A comparison with 10 Gbps system

In the recent years, development of services that require more bandwidth consumption (like broadcast TV, video on demand, mobile internet, etc.) is demanding a fast expansion of capacity. In such a perspective, the ability to carry 40/100 Gbps is inevitable. Operators have invested in large amounts on the infrastructure that now utilize 10 Gbps DWDM system but at the same time this rapid growth in data rates is forcing them to move forward to more promising technologies and this is the major drive behind the necessity of find a coexistence guidelines with 40/100 Gbps systems and keep 50-GHz ITU-T grid.

An important challenge is not to interfere with the operation of the existing 10 Gbps system and try to use the same resources for 40/100 Gbps systems.

For the proper performance of 40/100 Gbps in 10 Gbps infrastructure, the following features need to be adapted:

- **Modulation format**: the migration from the amplitude modulation (OOK) to phase modulation (DPSK for 40 Gbps and DP-QPSK for 100 Gbps) can provide a better resilience against non-linear impairments because signal amplitude remains almost constant. Because the points in the constellation diagram of both DPSK and DP-QPSK formats have equal distance to the origin, they offer constant signal power in the fiber making this modulation formats more tolerant to the fiber non-linear impairments than OOK. On the other hand, OOK does not require sophisticated modulator/ demodulator as 100 Gbps coherent detection.[36]
- **Dispersion:**

a. Chromatic dispersion penalty is squared when bit rate increases, meaning that it becomes 16 times for 40 Gbps and 100 times for 100 Gbps than what it is for 10 Gbps. Increase in chromatic dispersion is not problematic for 100 Gbps because it is compensated electronically in DSP but it will cause impairments in 40 Gbps system. Therefore like 10 Gbps, there is a need for inline compensators (DCMs and DCFs) and a Tunable dispersion compensator at the end of line. For 10 Gbps, a residual dispersion of $\pm$500 ps/nm (about 30 Km) can be tolerated but this figure is decreased to about 31 ps/nm (about 2 Km) which stresses the need to use a precise compensation at 40 Gbps. It is in the range of 50’000 ps/nm for 100 Gbps DP-QPSK. [31,36]

b. The common PMD figure for 10 Gbps is accepted as 10 ps .This requires the system to be able to tolerate a Differential Group Delay of 30 ps which will be the same limitation for 40 Gbps and 100 Gbps system, meaning that it becomes 2,5 ps and 1 ps respectively. Again compensation seems necessary for both of the figures. PMD compensator is used in 40 Gbps but it is handled electronically in the DSP module for 100 Gbps.

2.4.2 Compatibility and co-existence

In order to better utilize the capacity of current fiber optical network, carriers need to be able to transmit 10 Gbps NRZ-OOK signals along with 40 Gbps DPSK and 100 Gbps DP-QPSK signals on different neighboring channels of the same DWDM system with 50 GHz channels grid and make sure higher bit rate systems are compatible with 10 Gbps design rules.

40 Gbps and 100 Gbps systems have high signal power levels so the main impairment arises and that is XPM (phase noise distortion) occurring between 10 Gbps with 40 Gbps and 100 Gbps channels. CD and PMD tolerances are decreased in higher bitrates so they should be compensated in a network that transmits 10 Gbps signal along with 40 Gbps signal or 100 Gbps signal.

3 Details of migration scenario

3.1 Equipment

To verify the proper functionality and compatibility of the equipment which were currently used for 10 Gbps system with 40 Gbps and 100 Gbps, a series of tests and measurements needed to be undertaken. First, equipments and optical components are briefly introduced and then the technology which they work with is discussed. Component data sheets give more detailed information about each of the component used in my tests that are gathered in appendix 1 at the end of this report.

3.1.1 Transceivers

They are the most basic components in an optical network. Transceivers are "transmitter + receiver" in a same package. The pluggable transceiver has the ability to work in different wavelengths in C band or L band or both (in the Tunable versions, they support a wide range of wavelengths and the working wavelength can be easily chosen).They come in a variety of form factors, abilities and specifications. The ones used in the following measurements are 10 Gbps XFP and 40 Gbps 300 pin transceiver. They are used on the line side of the transmission.

- **XFP**: The module is a hot pluggable small footprint serial-to-serial data-agnostic multirate optical transceiver, intended to support Telecom (SONET OC-192 and G.709 "OTU-2") and Datacom applications (10 Gbps Ethernet and 10 Gbps Fibre Channel). Nominal data rates range from 9.95 Gbps, 10.31 Gbps, 10.52 Gbps, 10.70 Gbps, and the emerging 11.09 Gbps. The modules support all data encodings for these technologies. The modules may be used to implement single mode or multi-mode serial optical interfaces at 850 nm, 1310 nm, or 1550 nm.[37]

The used XFP for my test is made by "company A".

- **300-pin transceiver**: as naming suggests the connection to the board is via 300 pins and has a pair of input and output. It can be used for OOK and DPSK modulation. The only part that defers in two modulation format is just its modulator and demodulator units that are phase modulation/demodulation for DPSK and amplitude modulation/demodulation for OOK. The kind that has been used during tests in this report is a 43/44 Gbps NRZ-DPSK transponder. In the data sheet that is in appendix 1 (sub-chapter 5.1.2),it is evident that data is fed through 16 X 2.5 Gbps electric input signals and is multiplexed into one 40 Gbps electric signal and is converted to optical with help of a laser and the transmitted optical signal is phase-modulated. At the receiver side, it is demodulated using a delay line interferometer and pin photodetector and finally demultiplexed.

The 300-pin transceiver that was used in the coming tests is from “company O”.

3.1.2 Filters

In my tests, there were different devices that can mimic the effect of filters by cutting the spectrum and blocking a range of frequencies. Narrowing the spectrum causes signal distortion which is not desirable. Signal passing through a number of devices and components experienced filtering effects such as multiplexer/demultiplexer, wavelength blocker and Optical Interleaver Unit.

- **Multiplexer/Demultiplexer**: this module couples a single input to multiple output and multiple input to single output respectively. Each wavelength in the incoming signal’s spectrum entering the Mux module will be separated and exit monochromatically and similarly each of these wavelengths entering multiple port of demux will be combined again and continue to propagate in a single output. In the process of separation/recombination, a portion of the signal spectrum is cut and therefore the signal is filtered.

Mux/Demux used in my test is from “company B” and work based on Arrayed Waveguide Grating (AWG).

- **Wavelength Blocker**: It works like a tunable filter. It is capable of filtering (blocking) the signal spectrum. It is outlined in details in figure 3-1. When a number of tunable transmitters’ signals are combined and sent to Demux with the help of a splitter. At demultiplexer, each optical signal is decomposed into single wavelength components and each wavelength is passed through a switch. It is in these switches that one can keep a wavelength (let it pass through) or cancel a wavelength by simply opening the corresponding switch. Passed wavelength are again combined in a multiplexer and sent to an OCM for power level control. By using splitters, right before the demultiplexer unwanted wavelengths can be dropped and right after multiplexer some wanted wavelengths can be added to the main signal.

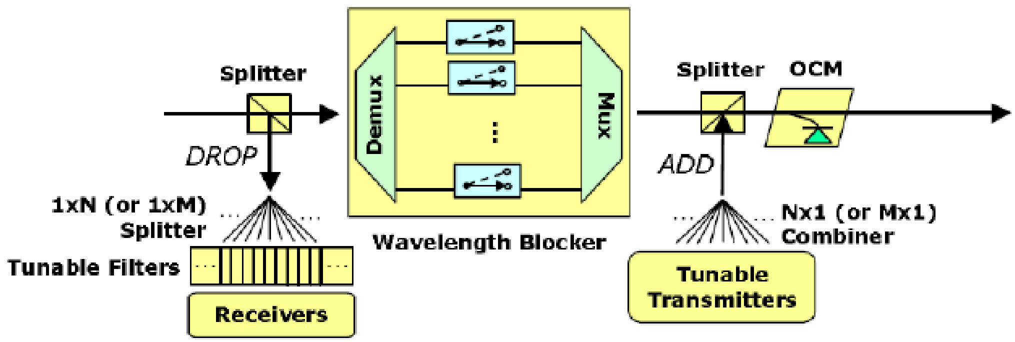


Figure 3-1: Wavelength blocker block diagram
[http://www.nordu.net/development/fiberworkshop2007/NNW03022007%20OSB.pdf]

The wavelength blocker module used in my test is from "company C". It can filter DWDM channels (50 GHz spacing) and also further filtering to a minimum of 20 GHz.

- **Optical Interleaver Unit**: This three-port passive device combines the set of input even channels (100 GHz spaced channels in 50 GHz grid DWDM) and odd channels (50 GHz spaced channels in 50 GHz grid DWDM) and has one output signal in which even and odd channels are arranged consecutively as shown in figure 3-2. Signal passing through OIU experiences a degree of filtration and its spectrum becomes narrower.

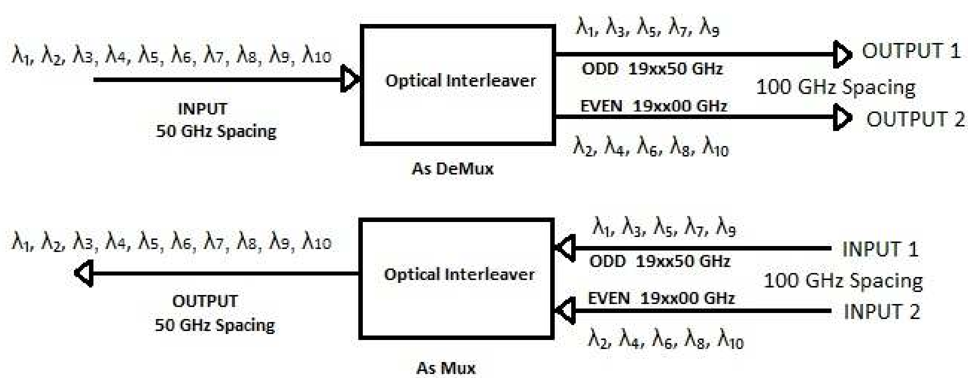


Figure 3-2: Building block for the interconnection of Mux/Demux and OIU

OIU used in my test worked based on Gire-Tournois etalon (GTE) from "company D".

3.1.3 Amplifiers

The power of an optical signal that enters the input port of an amplifier will experience an increase. The optical amplifier used in my test is Erbium Doped Fiber Amplifier is from "company E".

3.1.4 Wavelength Selective Switch (WSS)

It is the main component in a Reconfigurable Add Drop Multiplexer module which is a key component in optical telecommunication networks. It can route, attenuate or blocks any number of wavelengths on the optical path. Wavelength entering this device can be attenuated, blocked or simply passed through in any selection.

The switching engine for the WSS used in my tests is based on Liquid Crystal (LC) technology made by “company F”.

Polarization modulation is used in the switching engine of tested WSS and figures 3-3 to 3-5 illustrate them. It is based on the switching between two orthogonal polarization states of the input optical signal. The working principal of the LC switch is described in the following figures:

Input light will pass through without any change in polarization if LC cell is off (no voltage applied) but when it is on, it changes the polarization of light to the orthogonal state.

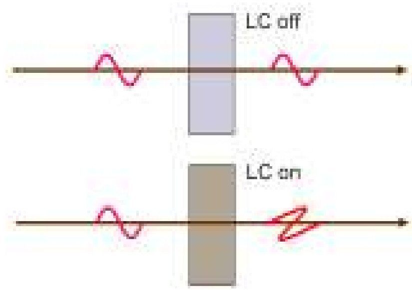


Figure 3-3: Changing polarization of incoming light by applying a voltage to LC cell
[http://www.fiberoptics4sale.com/wordpress/what-is-wavelength-selective-switchwss/]

Switching is done using a polarization beam splitter (a device that splits the signal into two orthogonally polarized beams) that changes the optical signal’s path according to its polarization state. Signal path will be different when the LC is off compared to the state where the LC is on and this is the basis of directing a signal to the desired path

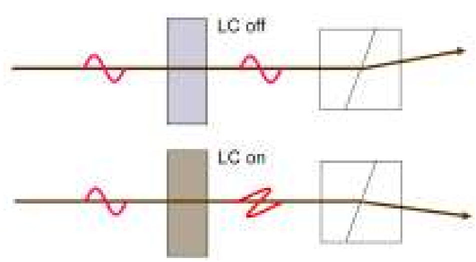


Figure 3-4: Signal switching based on polarization state
[http://www.fiberoptics4sale.com/wordpress/what-is-wavelength-selective-switchwss/]

To perform a binary switching, N liquid crystal (LC) cells can select among 2^N output ports. And an extra liquid crystal (LC) cell and polarizer can be used to provide attenuation.

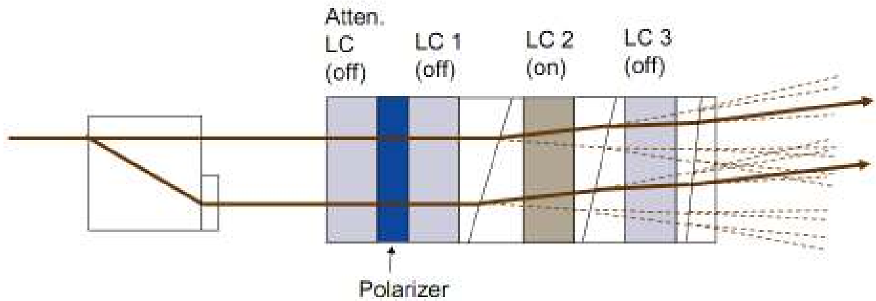


Figure 3-5: Binary switching configuration
[http://www.fiberoptics4sale.com/wordpress/what-is-wavelength-selective-switchwss/]

Company F's WSS that works in the range between ITU-T channel 18.5 to channel 58 (50 GHz spacing) was used in my test.

3.1.5 Optical Channel Monitor (OCM)

This device has the ability to monitor different parameters in an optical channel without directly measuring the bit sequence. An important parameter in a DWDM network is to keep track of each channel's power level and controlling it. Other elements measured by an OCM are wavelength and OSNR and has a critical role in control loops. It sets an alarm when wavelength of the channel is out of range and when the signal power is low or is about to be lost.

The first OCM module tested was from "company G" is a thick Volume Phase Grating to spatially separate different wavelength in a DWDM signal as shown in figure 3-6. A signal that contains a number of wavelengths is reflected to a lens to be collimated and from lens to a VPG where each wavelength is separated and directed (using a second lens) to the output.

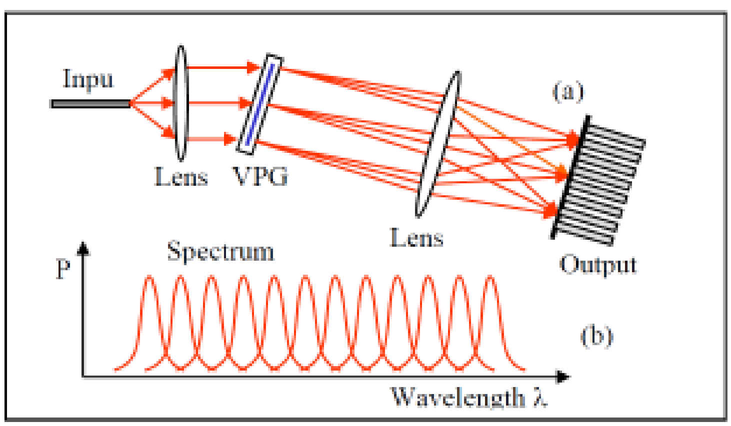


Figure 3-6: (a) Separation of different colors in a DWDM signal using VPG (b) their power spectrum
[Company G's VPG white paper]

Then, as figure 3-7 shows, ultra-sensitive InGaAs array detector will detect each channel's power and finally processed by a Digital Signal Processor unit.

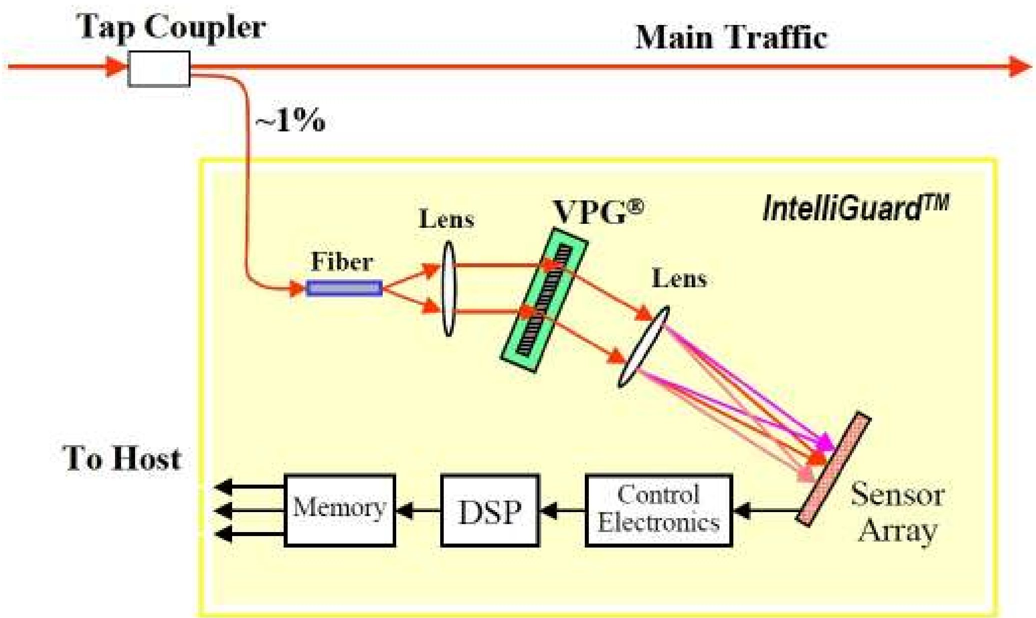
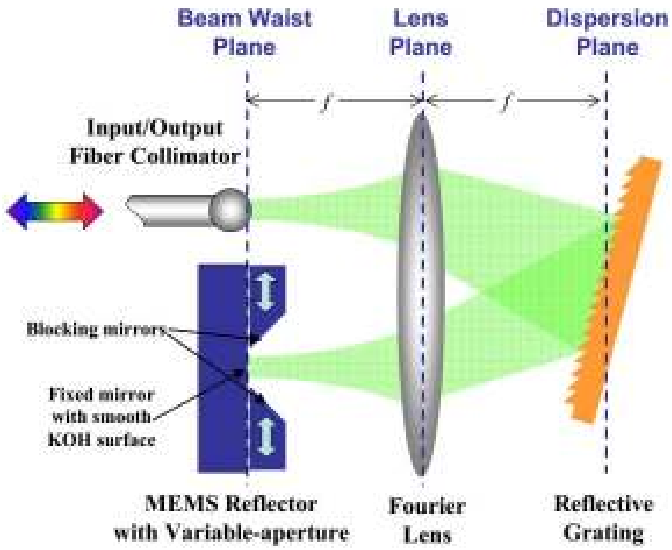


Figure 3-7: Functional schematic of company G's OCM module **[after OCM spec]**

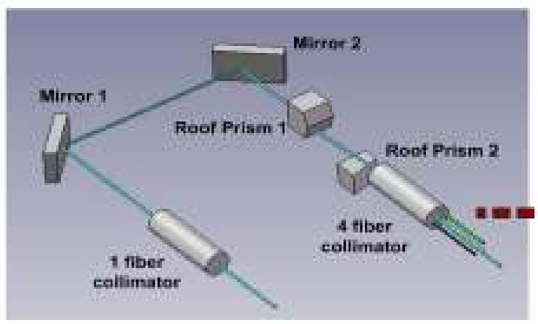
The next OCM is a 4 port and is made by "company H" and worked based on Micro Electro Mechanical Systems (MEMS) tunable filter, a photodetector and a 1x4 switch.

The passband of the filter is determined by the aperture of the MEMS mirror. The 4 input DWDM signals containing different wavelengths is passed through a 4x1 switch and reflected to a free-space grating and from that is reflected back to the MEMS variable aperture mirror. By increasing or decreasing the surface of aperture, desired spectrums of wavelengths are let through.

Then the output signal is directed to a photodetector and then to a processor unit. The output signal is then fed to a 1x4 switch to be sent in 4 output ports. The details are discussed in figures 3-8 and 3-9.



a)



b)

Figure 3-8: a) MEMS tunable filter schematic b) 4x1 switch
[39,photo switch]

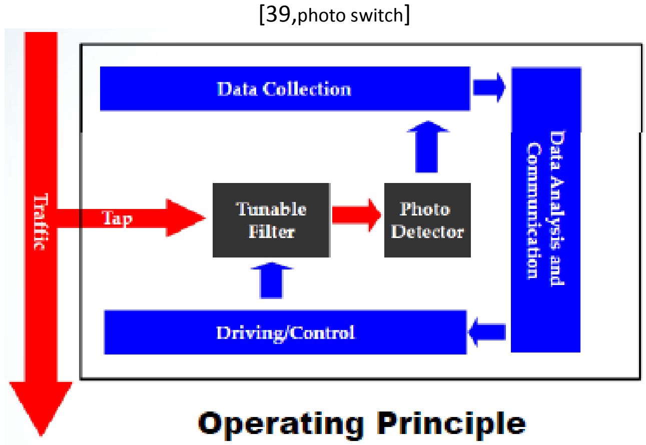


Figure 3-9: Schematic of OCM module
[Company H's spec]

The last OCM was MEMS-based with the technology described above from "company I" with an exception; it is single port therefore there is no need to 1x4 switch.

3.1.6 Dispersion Compensating Module (DCM)

It is a finished module that compensates for signal dispersion created along the optical fiber link. Dispersion compensating fiber can compensate for the dispersion using its negative dispersion characteristic (negative slope). Spectrum of a signal that passes through a certain length of DCF is compressed at the output of fiber. In general, signal power is more attenuated in a DCF than in equal length of ordinary fiber and also, DCF introduces PMD to the signal.

DCM used in my test is made by “company J” and consists of a fixed length of dispersion compensating fiber in a box.

3.1.7 Tunable Dispersion Compensator (TDC)

This device, like DCM, can compensate for the dispersion created through the fiber optical link. Also, tunability helps to compensate for all the dispersion and leaves no residual dispersion uncompensated.

The TDC module that I used for my tests was from “company K” and used Gire-Tournois Etalons as the method of compensation.

Gire-Tournois etalon is practically a Fabry-Pérot etalon with one surface is 100% reflective and the other partially reflective. Light hitting on the partially reflective surface will experience a phase shift depending on the wavelength of the light. This phase shift can be thermally controlled by changing the thickness of the surface, its reflectivity changes [40] TDC from company K works based on this technology. There are 12 cascaded single etalons in it that each has an individual group delay response. The orientation of the slope is determined by where in spectrum is cascaded group delay responses distributed. Figure 3-10 shows individual and synthesis role of each etalon in forming a dispersion slope.

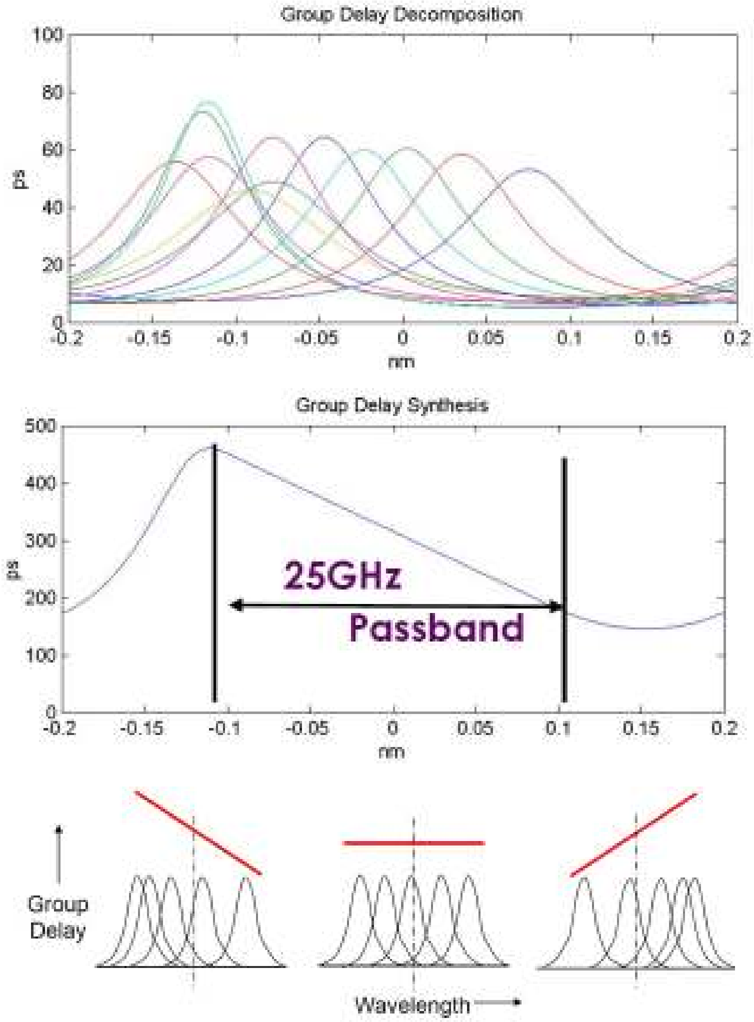


Figure 3-10: Group Delay Response for individual etalons (up) and cascaded etalons (middle) and different slopes resulted from different distribution of GDR curves
[company K's marketing document]

3.2 Experimental results

The aim of the tests performed on the equipments mentioned in the previous sub-chapter was to evaluate and possibly verify their credibility and compatibility to 10 Gbps OOK, 40 Gbps DPSK and 100 Gbps DP-QPSK modulation formats on.

Purpose of each test, test method, the target parameter to be evaluated and the outcomes of each test are presented according to desired bit rate and modulation format of operation. The achieved goals or failures and their possible reason are briefly discussed in the next chapter. All tests have been carried out with following systems:

- 40 Gbps DPSK system from "company L and M".
- 100 Gbps DP-QPSK (coherent det.) system from "company N".

3.2.1 BER versus OSNR for 40 G and 100 G

- **The purpose of this test**: was to evaluate the effect of neighboring channels on the center channel. In this test, the two neighboring channels' signals that have similar bit rates are positioned 200 GHz, 100 GHz and finally 50 GHz higher and lower on the spectrum according to the signal on the center channel which has different bit rate comparing to its neighbors. For example, if we suppose the center channel being positioned on channel 939 (ITU-T DWDM grid), the neighboring channels are on (channel 937 - TARGET channel - channel 941) for 200 GHz separation, on (channel 938 - TARGET channel- channel 940) for 100 GHz spacing and on (channel 938,5 - TARGET channel - channel 939,5) for 50 GHz spacing.
- **Test method**: center signal and two neighbor signals are sent through the setup in figure 3-11. BER is read from the Graphical User Interface of the signal generator of the center channel. OSNR is read from spectrum analyzer. Each wavelength has an independent PRBS sequence.

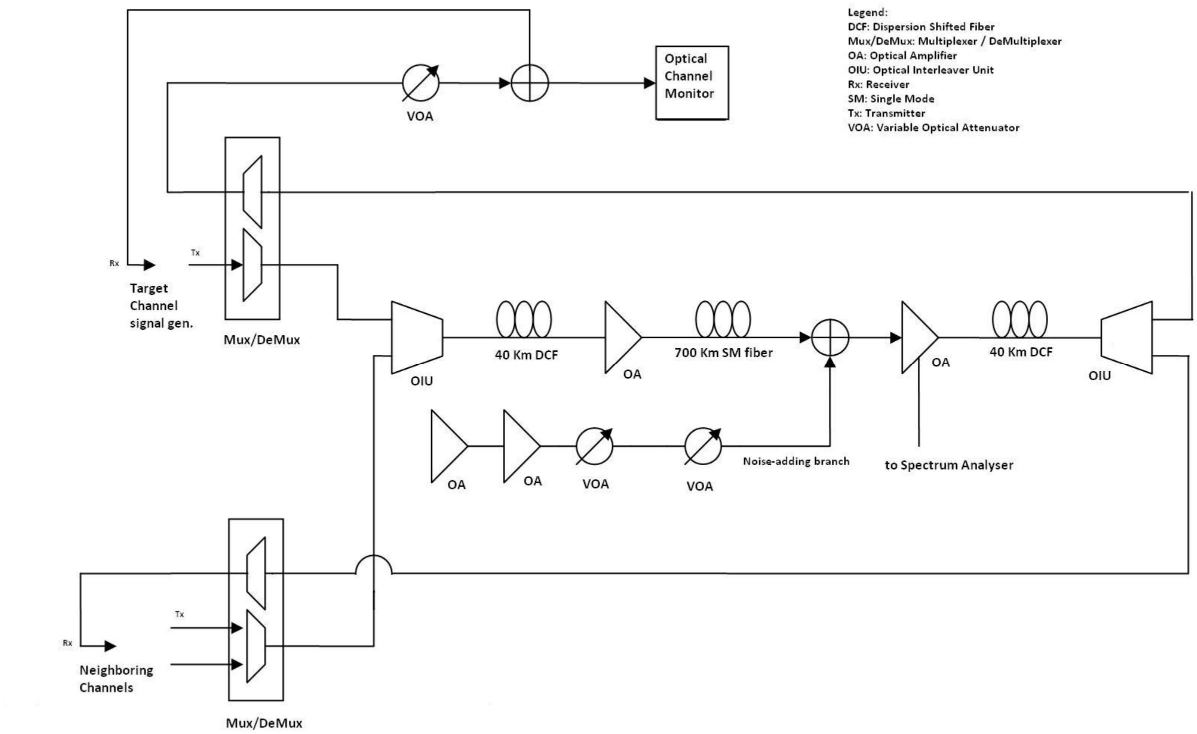


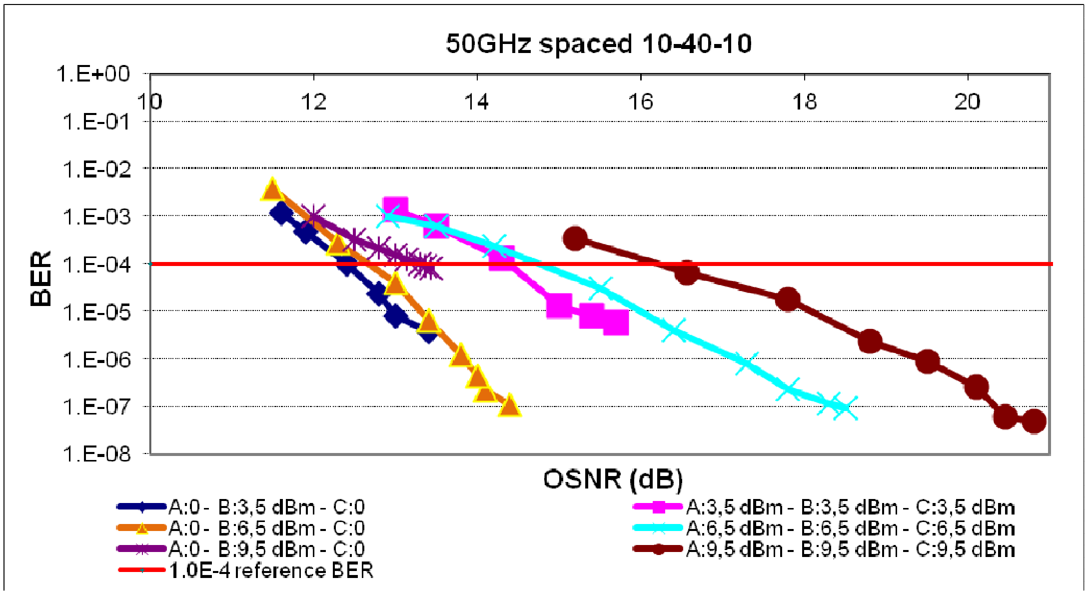
Figure 3-11: Test setup

- **Target of the test**: is to evaluate the effect of neighboring channels on center channel's BER versus changes in OSNR.
- **Outcomes**:

BER vs. OSNR for 200 GHz, 100 GHz and 50 GHz spacing:

Channel A (neighbor-10 G) - Channel B (target-40 G) - Channel C (neighbor-10 G)

First, one target channel carrying 40 Gbps signal and two neighbor channels that are positioned on 50 GHz separation (one with 50 GHz higher frequency and the other with 50 GHz lower frequency) each carrying 10 Gbps signals are fed into odd and even multiplexer/demultiplexer units. The output of each multiplexer are combined using odd and even ports of optical interleaver units and a single output from OIU is sent through the link. Extra noise is added by two EDFAs. Finally, the target signal is returned back to receiver port of 40 Gbps signal generator for BER measurement. Target signal is sent alone in the link to have a reference for better investigating the unwanted effects of neighbor signals on the target signal and to find the OSNR penalty that they will impose on the target signal. In figure 3-12 either all three signals have similar power level or just target signal has a specific power level but two neighbors have no power at all. Three different power levels for this test are 3,5 dBm, 6,5 dBm and finally 9,5 dBm.

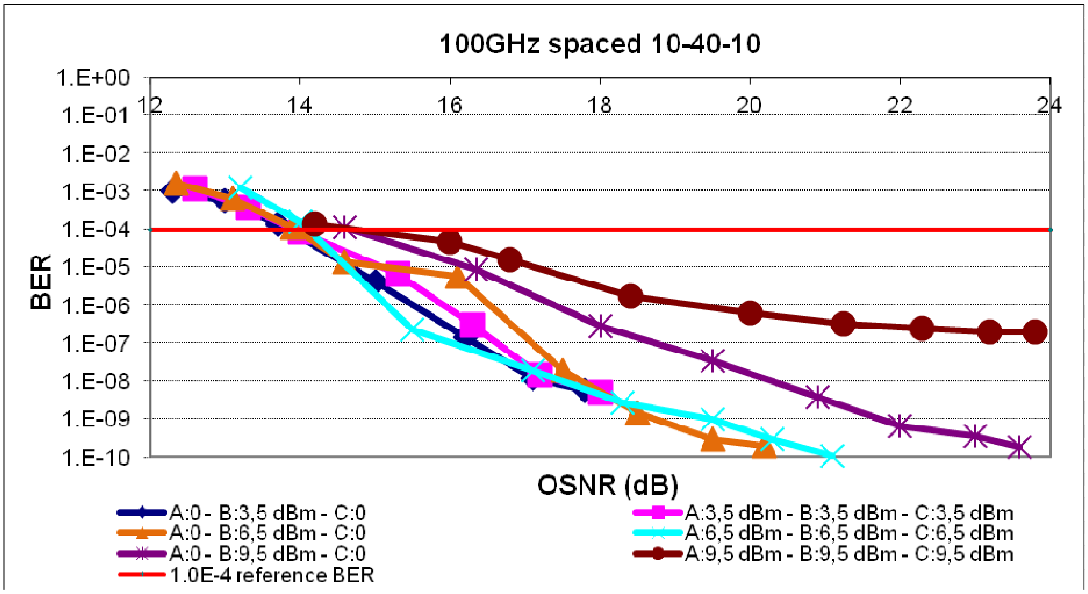


Input power level	**3,5 dBm**	**6,5 dBm**	**9,5 dBm**
OSNR penalty due to unwanted effects of neighboring channels	2,0 dBm	2,0 dBm	2,9 dBm

Figure 3-12: 50 GHz spaced A (10G) – B(40G) – C(10G) and OSNR penalties for each power level

Single input curves have very low OSNR level at reference BER (1,0E-4) which seems unrealistic. As it was expected, lower input power level (3,5 dBm) has better OSNR and also smaller OSNR penalty compared to high input power level curve (9,5 dBm). The OSNR penalty is caused by non linear impairments that neighboring 10 Gbps signal impose on out 40 Gbps target signal. The OSNR penalty increases with increase in input power level because of higher interaction of nonlinear impairments in higher input powers. Also, nonlinear impairments are credible for the BER floor that is visible in the curve in which all three signals have 9,5 dBm of input power.

By farther increase in neighbor-target signals separation, we expected to see that nonlinear impairment effects are becoming less and less critical because of the distance. Therefore, increase the separation to 100 GHz and made exactly the same set of measurements. Results of increased separation (100 GHz) curves can be seen in figure 3-13.

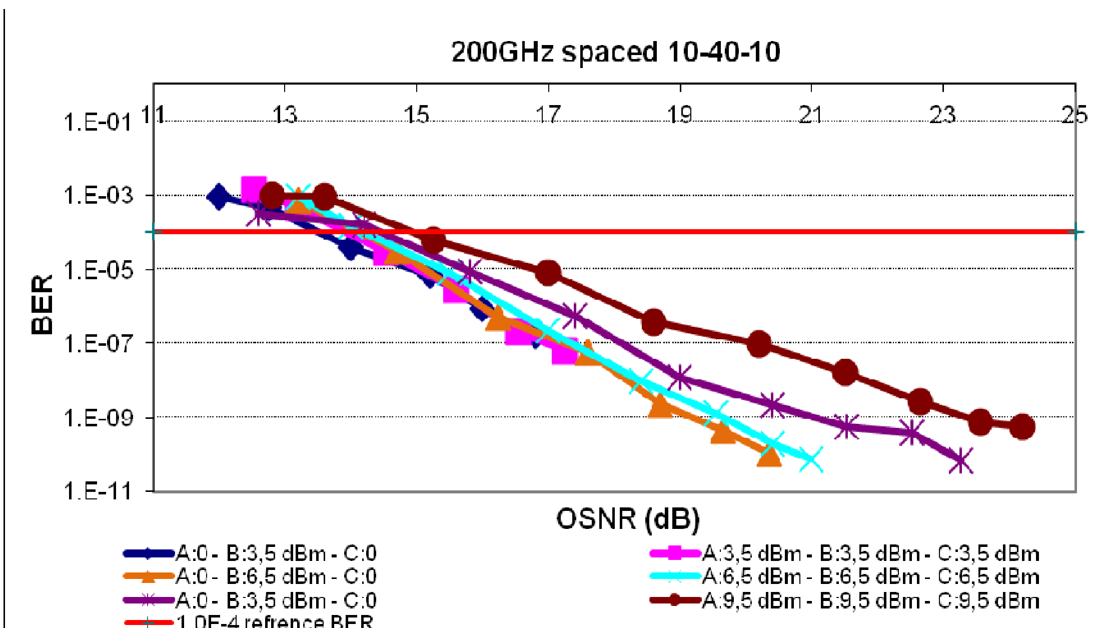


Input power level	3,5 dBm	6,5 dBm	9,5 dBm
OSNR penalty due to unwanted effects of neighboring channels	< 0,1 dBm	< 0,1 dBm	< 0,1 dBm

Figure 3-13: 100 GHz spaced A (10G) – B(40G) – C(10G) and OSNR penalties for each power level

In this test, OSNR levels are increased to 14 dBm and are more realistic. The OSNR penalties are very small now meaning that the unwanted effects from neighboring channels are reduced. But still BER floor for high input power level (9,5 dBm) is present.

To see how signals interfere with each other in larger separations, 200 GHz spacing was taken as the new separation. The same tests as the two previous cases were carried out on the signal. The results are shown in figure 3-14.



Input power level	3,5 dBm	6,5 dBm	9,5 dBm
OSNR penalty due to unwanted effects of neighboring channels	0,5 dBm	< 0,1 dBm	0,5 dBm

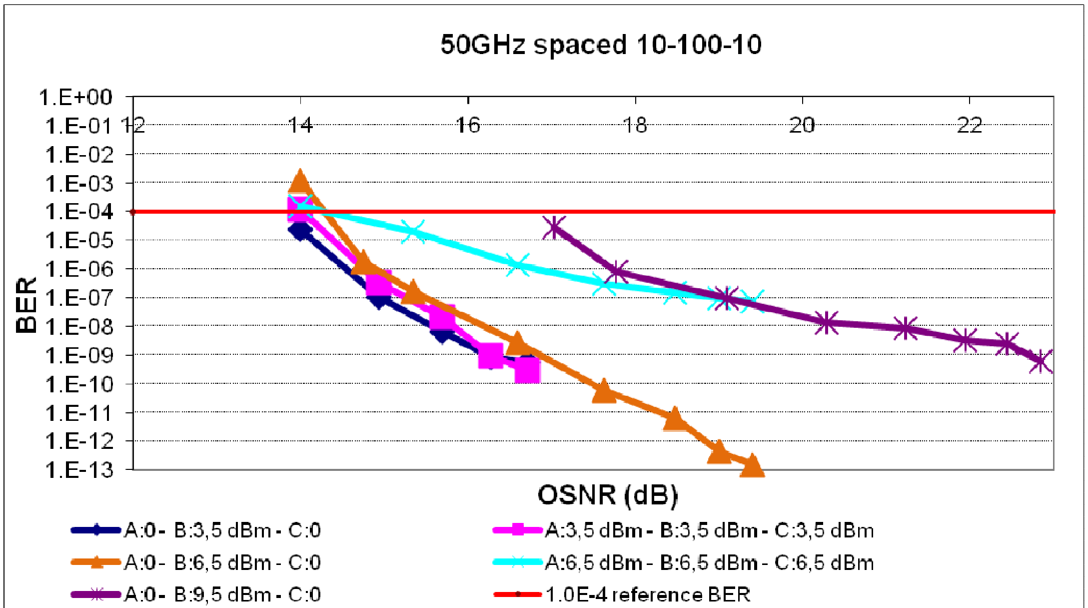
Figure 3-14: 200 GHz spaced A (10G) – B(40G) – C(10G) and OSNR penalties for each power level

In 200 GHz, OSNR penalties are smaller than 50 GHz case but larger than 100 GHz case. Also, OSNR levels are lower than 100 GHz but larger than 50 GHz case. BER floor is still maintained.

Channel A (neighbor-10 G) - Channel B (target-100 G) - Channel C (neighbor-10 G)

The same setup and power levels and spacing as the first case was applied to this test with exception of the target channel carrying 100 Gbps signal.

Figure 3-15 shows the result of test for 50 GHz separation

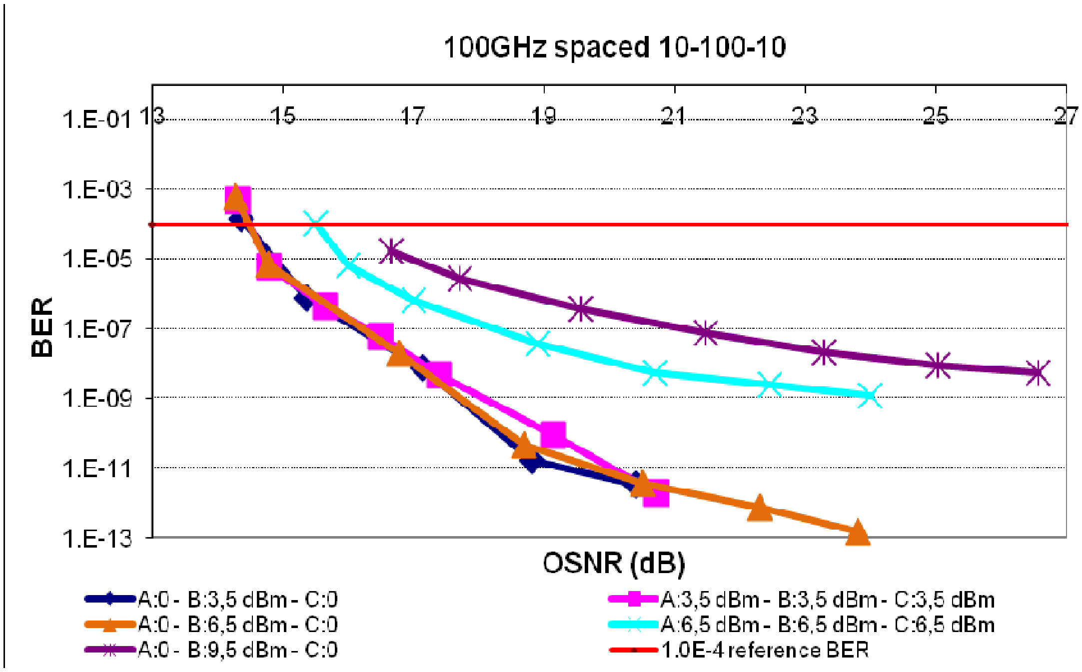


Input power level	3,5 dBm	6,5 dBm	9,5 dBm
OSNR penalty due to unwanted effects of neighboring channels	0,3 dBm	0,2 dBm	-

Figure 3-15: 50 GHz spaced A (10G) – B(100G) – C(10G) and OSNR penalties for each power level

No BER could be measured at 9,5 dBm because of nonlinear effects from two neighbor channels increased errors. OSNR penalties are smaller for 10-100-10 than 10-40-10.

Figure 3-16 shows the case in which the separation is increased to 100 GHz.

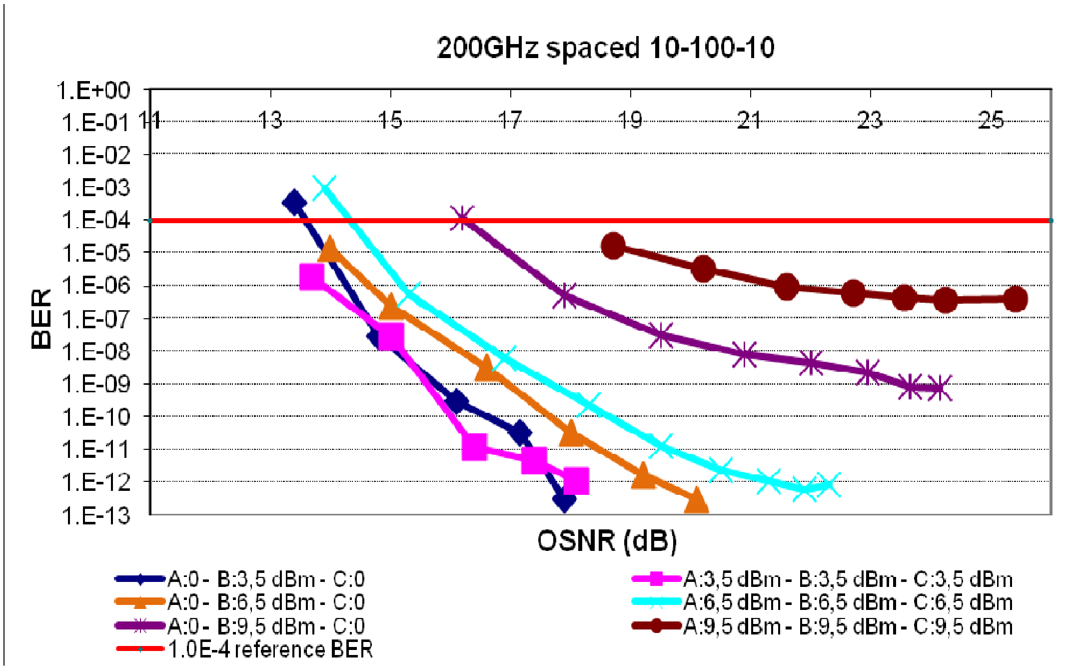


Input power level	**3,5 dBm**	**6,5 dBm**	**9,5 dBm**
OSNR penalty due to unwanted effects of neighboring channels	< 0,1 dBm	1 dBm	-

Figure 3-16: 100 GHz spaced A (10G) – B(100G) – C(10G) and OSNR penalties for each power level

BER floor exists for both 6,5 dBm and 9,5 dBm signal. For input power of 3,5 dBm, there is almost no penalty but for 6,5 dBm, OSNR penalty is even larger than that for 50 GHz spacing. Again because of high non linear impairments interaction, there is no OSNR curve for 9,5 dBm with neighbors.

200 GHz separation for 10-100-10 is shown in figure 3-17.



Input power level	3,5 dBm	6,5 dBm	9,5 dBm
OSNR penalty due to unwanted effects of neighboring channels	0,25 dBm	0,7 dBm	1,8 dBm

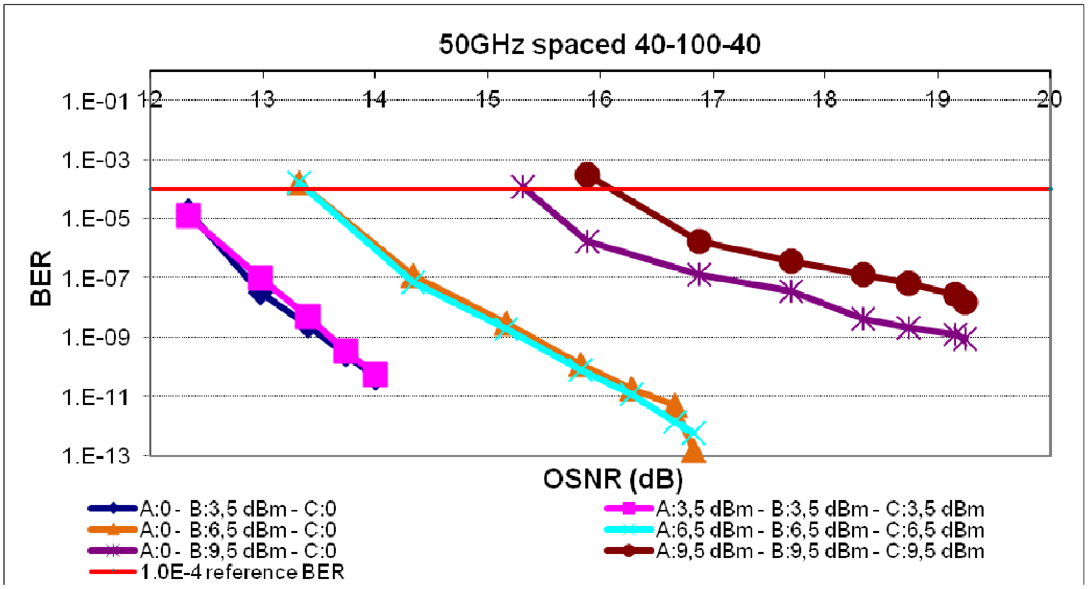
Figure 3-17: 200 GHz spaced A (10G) – B(100G) – C(10G) and OSNR penalties for each power level

With 200 GHz separation, the unwanted effects of nonlinear impairments are not that severe so BER vs. OSNR curve for input power of 9,5 dBm with two 10 Gbps neighbors is measured. BER floor also exists and has smaller slope compared to 50 GHz and 100 GHz case because of high input power and large nonlinear impairments. OSNR penalties are also large.

Channel A (neighbor-40 G) - Channel B (target-100 G) - Channel C (neighbor-40 G)

The last set of measurements is 40-100-40 with 50, 100 and 200 GHz spacing. It is especially interesting because both target and neighbor signals are phase modulated. Fluctuations in intensity can cause cross phase modulation between 40 Gbps signals as neighbors and 100 Gbps signal as target signal which degrades OSNR and creates OSNR penalty.

In figure 3-18, 50 GHz spaced 40-100-40 is shown.

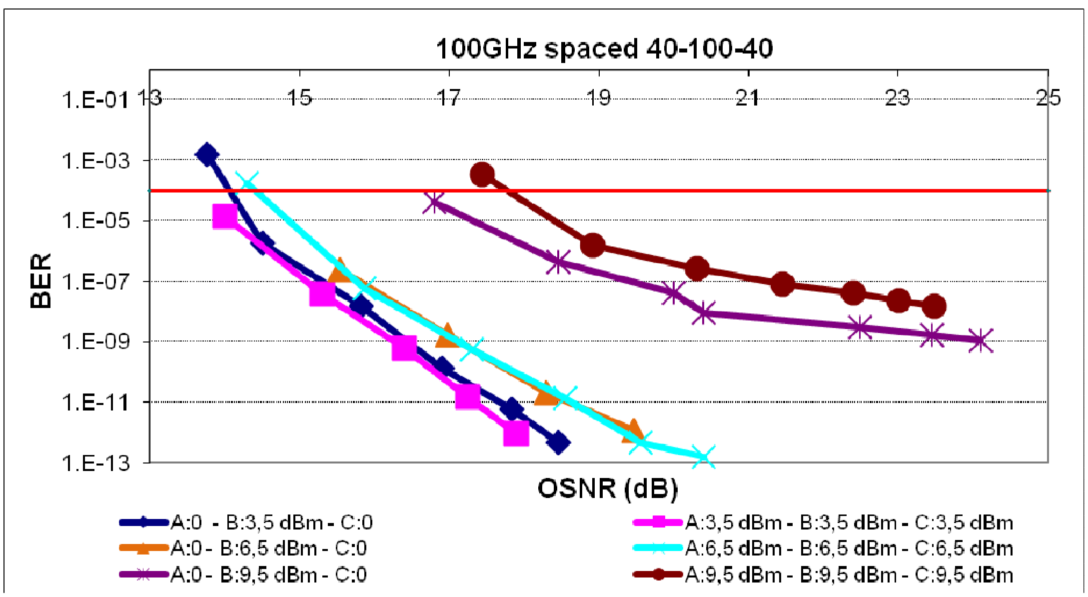


Input power level	3,5 dBm	6,5 dBm	9,5 dBm
OSNR penalty due to unwanted effects of neighboring channels	< 0,1 dBm	< 0,1 dBm	0,9 dBm

Figure 3-18: 50 GHz spaced A (40G) – B(100G) – C(40G) and OSNR penalties for each power level

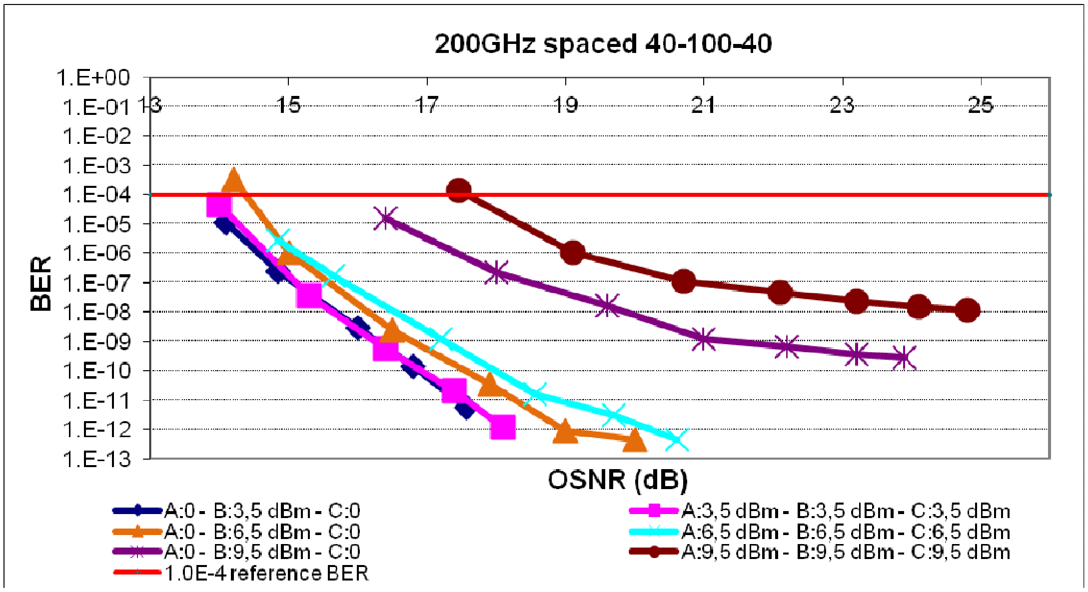
OSNR penalty is much less than when neighbor channels were 10 Gbps. There is a BER floor for high input power (9,5 dBm).

100 GHz and 200 GHz separations are shown in figure 3-19 and figure 3-20.



Input power level	3,5 dBm	6,5 dBm	9,5 dBm
OSNR penalty due to unwanted effects of neighboring channels	0,3 dBm	< 0,1 dBm	1,1 dBm

Figure 3-19: 100 GHz spaced A (40G) – B(100G) – C(40G) and OSNR penalties for each power level



Input power level	3,5 dBm	6,5 dBm	9,5 dBm
OSNR penalty due to unwanted effects of neighboring channels	< 0,1 dBm	< 0,1 dBm	1,5 dBm

Figure 3-20: 200 GHz spaced A (40G) – B(100G) – C(40G) and OSNR penalties for each power level

Corresponding OSNR level for each input power is the same at 100 and 200 GHz separation. OSNR penalty at 9,5 dBm of input power is large for both separations.

3.2.2 The effects of filtering on 40 Gbps and 100 Gbps signals

- **The purpose of this test**: was to evaluate the effect of signal spectrum filtration by passing through components that have bandwidth smaller than the 40 Gbps and 100 Gbps signals. These components are Mux/Demux, WSS, OIU and finally WavelengthBlocker.
- **Test method**: The following test setup in figure 3-21 was used in general. For "no Filter", the signal was coupled directly to optical spectrum analyzer. For the other arrangements, involved components were cascaded and the output signal was fed to the spectrum analyzer.

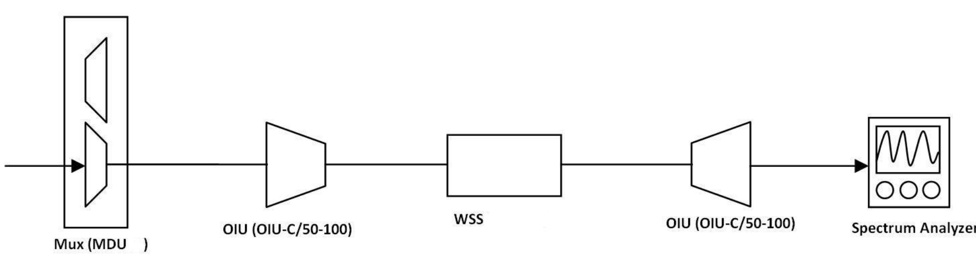


Figure 3-21: Filtering effect measurement setup

- **Target parameter**: is to study the effect of narrowing of bandwidth on the performance of the signal
- **Outcomes:**

Unfiltered spectrum of 40 Gbps and 100 Gbps are shown in figure 3-22. The green line shows the 3-dB reference and by that, 3-dB band width can be calculated as ~33 GHz for 40 Gbps and ~27 GHz for 100 Gbps signals.

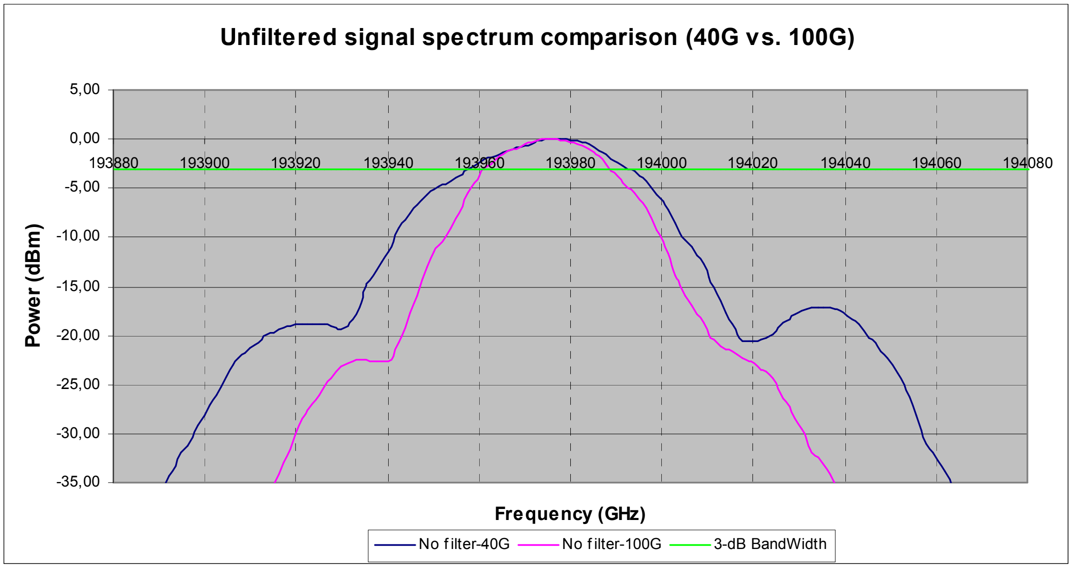


Figure 3-22: Unfiltered 40 G and 100 G signal spectrum

The first test is to find the effect of bandwidth narrowing on 40 Gbps signal. Signal was passed through a series of cascaded components like multiplexer, wavelength selective switch, optical interleaver units to check their filtering effect on signals spectrum and the resulting spectrum could be seen on spectrum analyzer. WSS cascaded with either of other devices determines the tightest filtering with 3-dB band width of ~28 GHz.

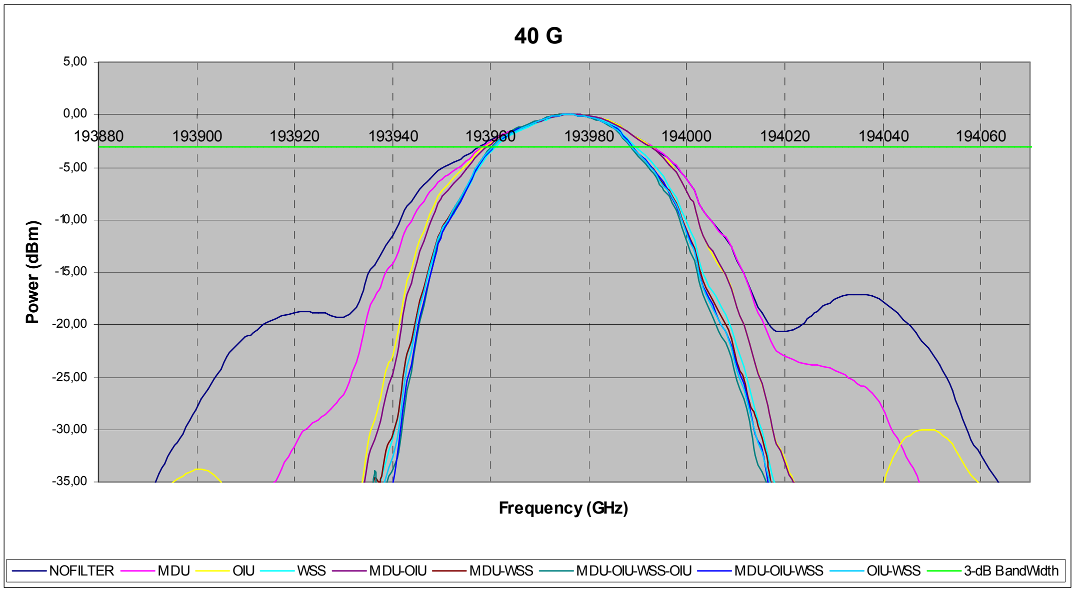


Figure 3-23: Filtering effect of different components on 40 G signal

For 100 Gbps signal, the same test was carried out. Again, it was WSS cascaded with OIU or multiplexer that determined the filter with minimum band width which in this case is ~26 GHz.

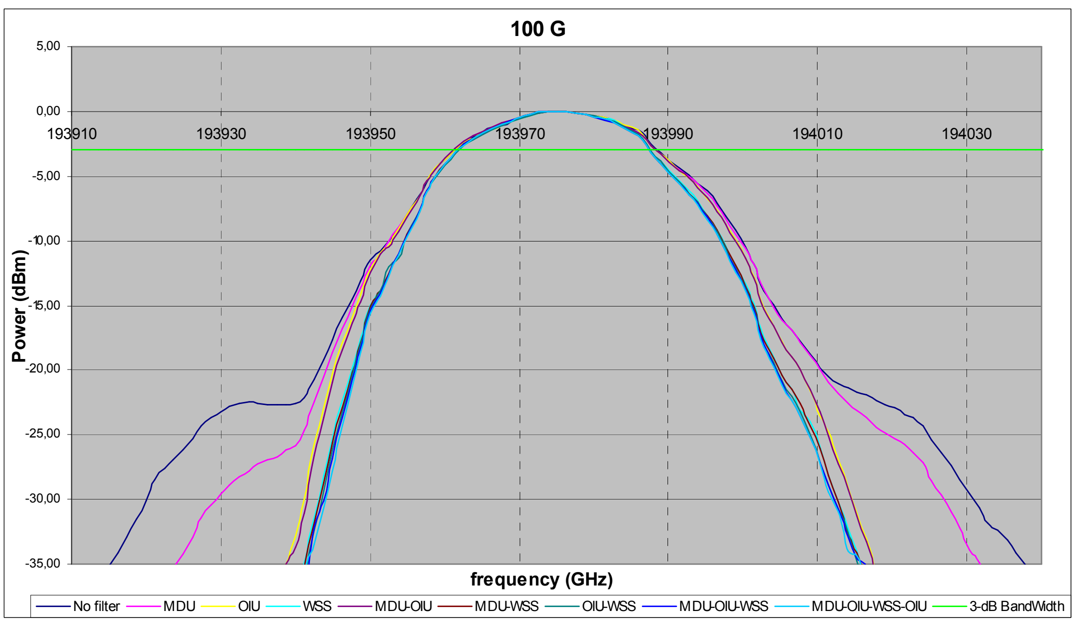


Figure 3-24: Filtering effect of different components on 100 G signal

3.2.3 The effects of filtering on BER versus OSNR

- **The purpose of the test**: was to study the effect of decreasing bandwidth on BER versus OSNR performance for 40 Gbps and 100 Gbps signals
- **Test method**: basically the setup in figure 3-11 was used but with different components as is indicated in the figure 3-21. The narrowest filter bandwidth belongs to wavelength blocker with 30 GHz bandwidth.

- **Target of the test**: To verify the destructing effect of narrow bandwidth on BER versus OSNR value for 40 Gbps and 100 Gbps signals.
- **Outcomes:**

To evaluate the effect of filtering on BER vs. OSNR, cascaded devices like OIU, multiplexer/ demultiplexer and WSS was used. Also to squeeze the signal even more, Wavelength Blocker was used that has the ability to filter down to 20 GHz. Figure 3-25 and 3-26 show the filter profiles used in this test.

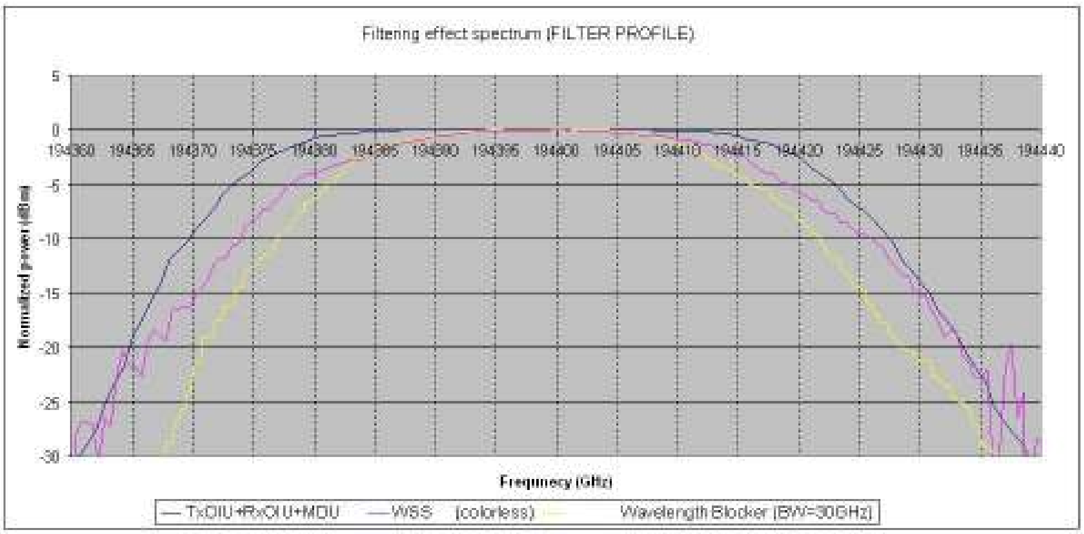


Figure 3-25: Filter profile

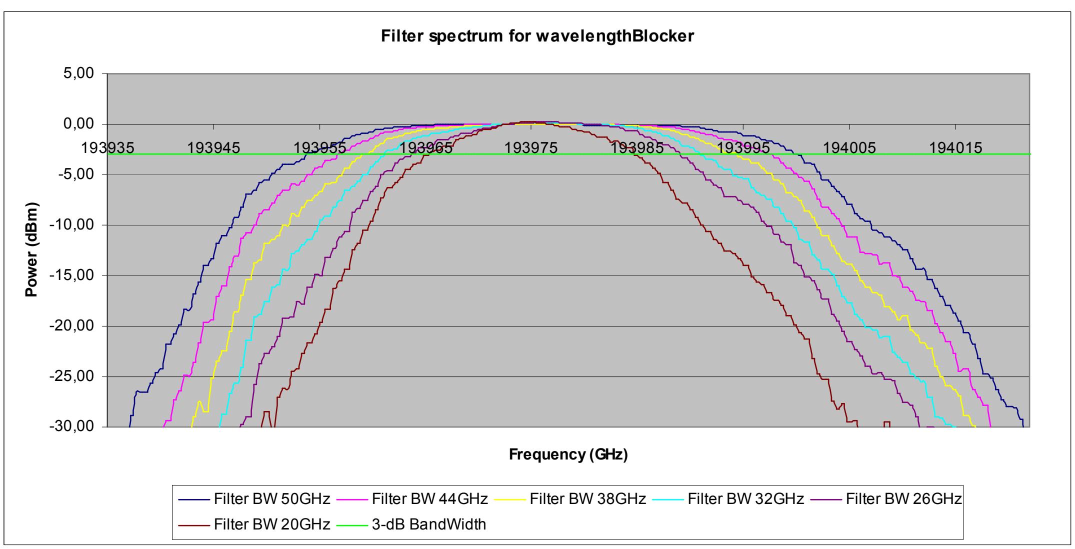


Figure 3-26: Filter profile from 50 GHz to 20 GHz

First, 40 Gbps signal was fed to multiplexer unit. After passing through a number of attenuators and amplifiers and 700 Km of single mode fiber; its BER versus OSNR was measured. The result can be seen in the figure 3-27.

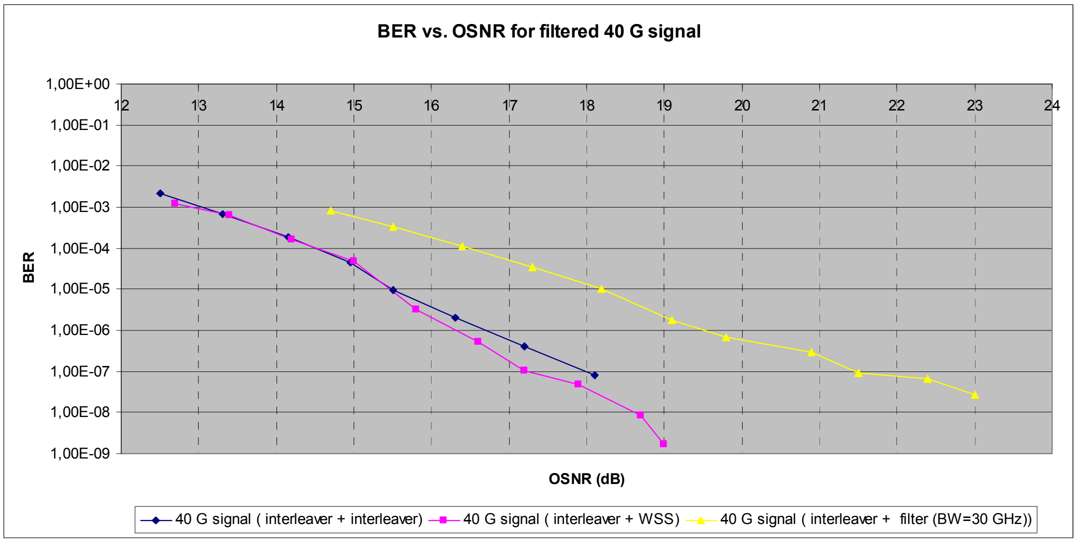


Figure 3-27: BER vs. OSNR for filtered 40 G signal

OSNR level is degraded for filtering tighter than 33 GHz. The OSNR penalty at tight filtration is about 2 dB. The reason is that some significant portion of signal (unfiltered bandwidth equal to 33 GHz is cut that leads to increase in BER and degradation of OSNR.

100 Gbps signal was also subjected to a similar test to evaluate the effect of filtering on OSNR performance of the signal. As can be seen in figure 3-28 filtering even as tight as 32 GHz has negligible effect on OSNR levels.

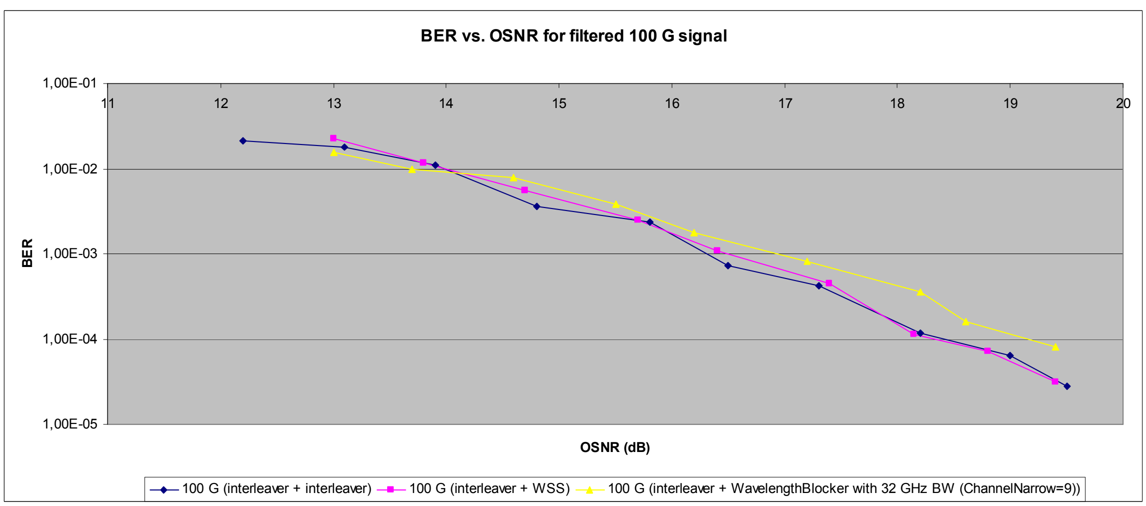


Figure 3-28: BER vs. OSNR for filtered 100 G signal

There is a very small penalty in BER when decreasing the filter bandwidth from 46 GHz down to 30 GHz.

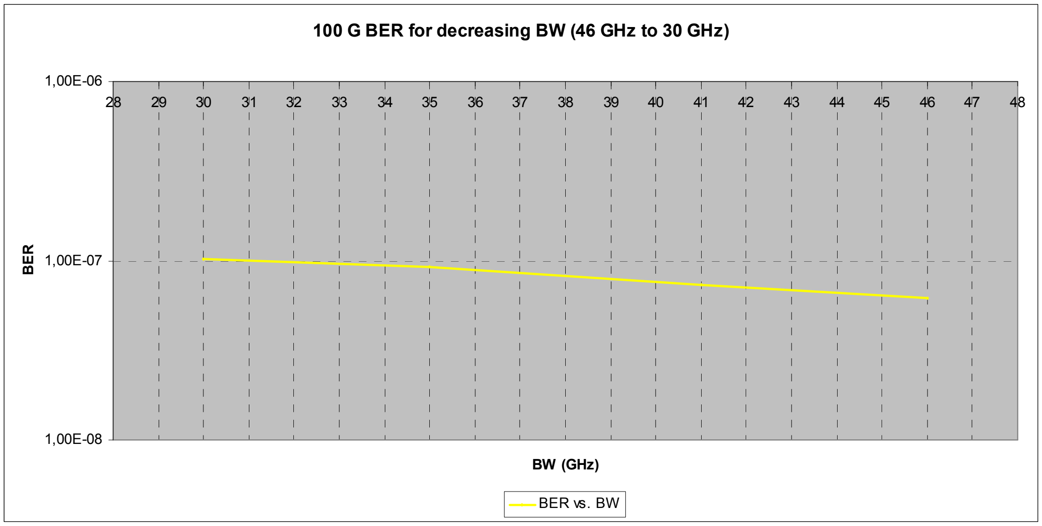


Figure 3-29: BER penalty for decreasing BW from 46 GHz to 30 GHz

WavelengthBlocker from company C's bandwidth decrease is stepwise, therefore the next bandwidth setting is 26 GHz which is smaller than ~28 GHz (unfiltered bandwidth of 100 Gbps signal) so the signal is lost with filtration tighter than 30 GHz and no BER can be achieved for this filtration.

3.2.4 OCM performance

- **Purpose of the test**: was to evaluate the performance of three OCM modules from company G, H and I. The aim is to see the smallest difference between power levels detected by the OCM and a calibrated power meter. Also, it is desirable that OCM is able to detect very low light power levels.
- **Test method**: setup is the same as in figure 3-11. For multiport OCMs, measurements were carried on one of the ports.
- **Target parameter**: to have the minimum difference between power levels detected by OCM to that of a calibrated power meter.
- **Outcomes:**

Company G

This OCM device has two output ports. Figure 3-30 shows the test setup used to evaluate the performance of this OCM

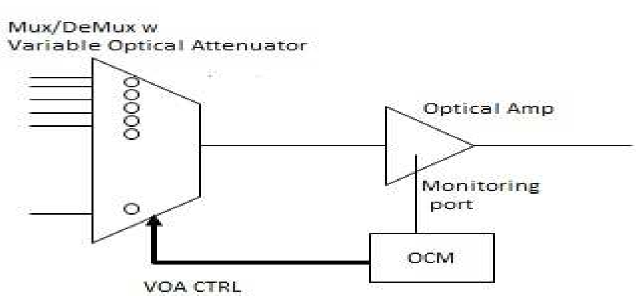


Figure 3-30: Test setup for company G OCM

The launched signal (10 Gbps and 40 Gbps) were fed to the multiplexer module and from there to an EDFA. The OCM was connected to the monitoring port of the EDFA. There was a control loop that could balance the launch signal's level by help of in-built optical attenuator in the multiplexer .To verify the effect of the signal wavelengths on the performance of the OCM, three different channels (one in the upper C band, one in the middle and one in the lower C band) were chosen. Power levels detected by OCM (10 Gbps signal and 40 Gbps signal) and a calibrated power meter are presented in figure 3-31.

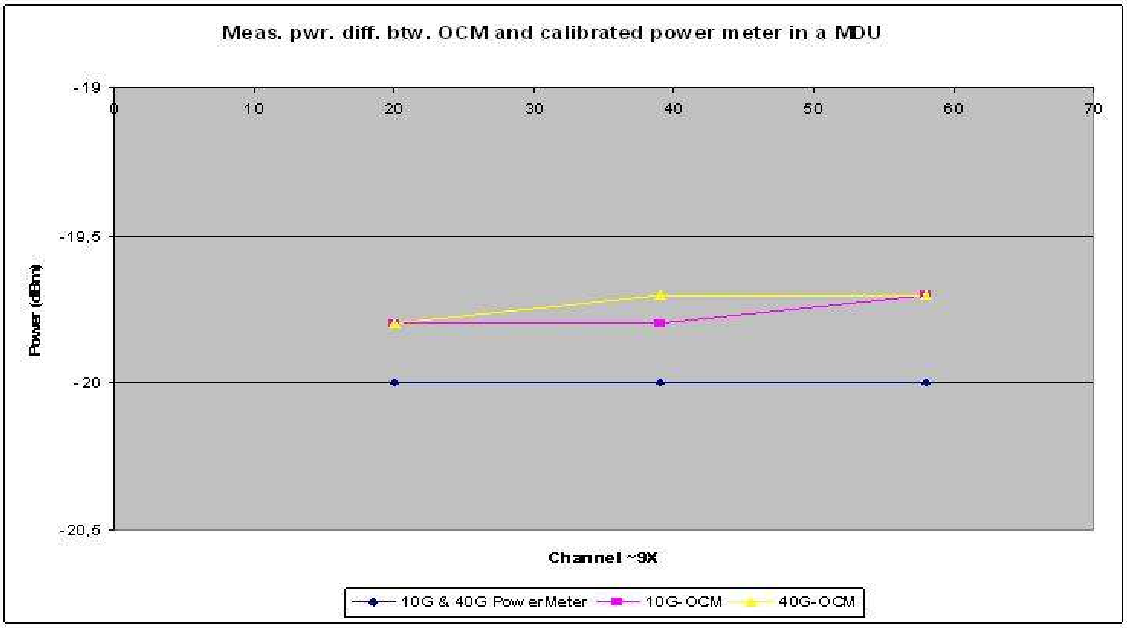


Figure 3-31: Power difference between OCM and calibrated power meter for 10G and 40G signals

The difference between the power levels detected by OCM and a calibrated power meter is about 0,3 dB.

In the next test, three signals, arranged in three neighboring channels with 100 GHz spacing, are fed to the multiplexer to check the effect of neighboring signals on the target signal in the middle to evaluate the sensitivity of OCM. By keeping the neighboring signals' power levels constant, target signal's power level is continuously decreased until it is no longer reported by the OCM. Test is performed with the following arrangement: 10G-10G-10G, 10G-40G-10G and 40G-10G-40G

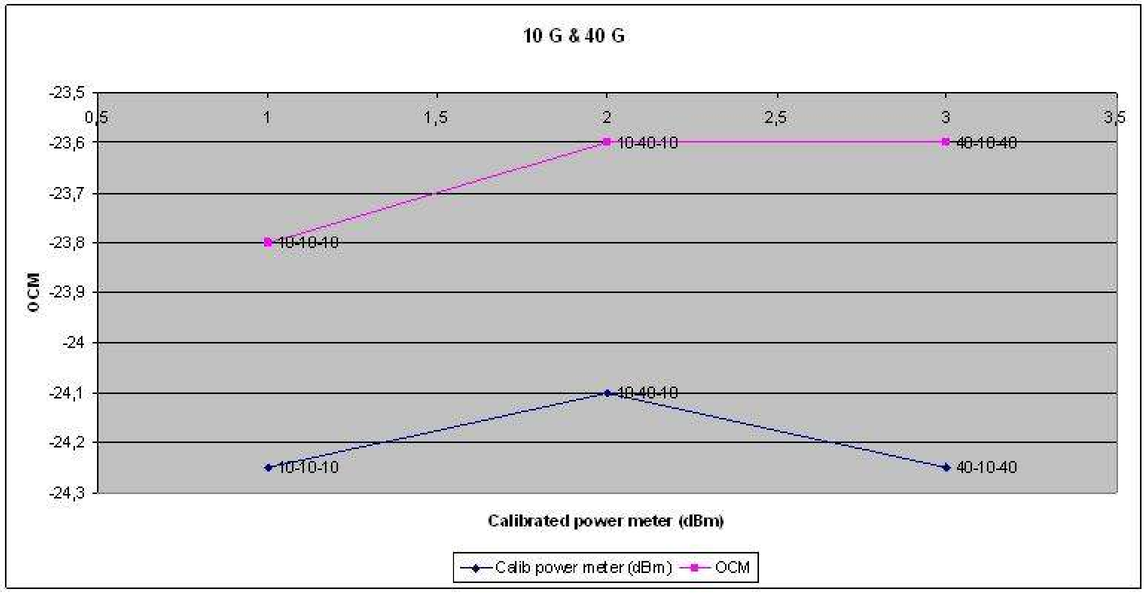


Figure 3-32: Adjacent channels' power effect on center channel for 10G and 40G

Difference is largest when two neighboring signals are 40 Gbps and the target channel is 10 Gbps because two neighbors are much broader than target channels spectrum and by decreasing the power level of target channel, it will disappear in the tails of two neighbors.

Company H

This OCM is a four port. Test setup is as described in figure 3-11. Measurements are done with port one of OCM. At 10Gbps, 40Gbps and 100 Gbps, three different wavelengths have been launched to the setup. Without filter (NoF), with Mux/Demux and finally with OIU.

Figure 3-33 shows the power level of each arrangement measured by OCM versus the same value measured by a calibrated power meter for 10 Gbps signal. The ideal performance should be the closest to the blue line in. Figure 3-34 shows the same measurement results with difference for each case in a more graphical way. It can be seen that there an offset in power differences.

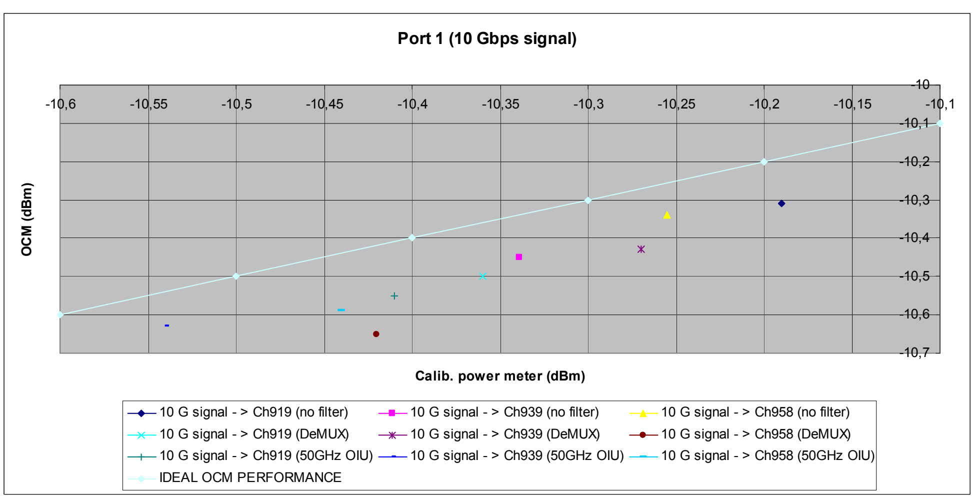


Figure 3-33: 10G signal, OCM detected power vs. calibrated power meter for different conditions

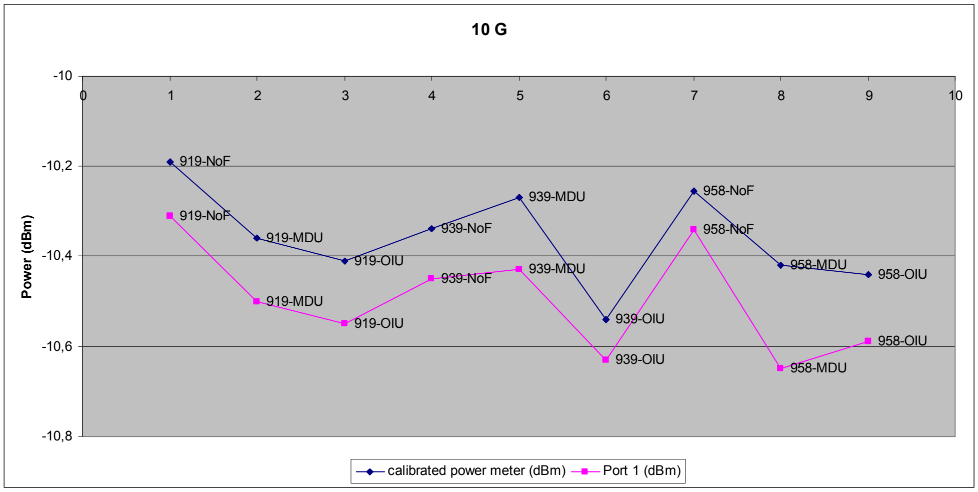


Figure 3-34: 10G signal, difference with calibrated power meter for different conditions

Figures 3-35 to 3-38 show the result of the same measurements but with a 40 and 100 Gbps signal instead of 10 Gbps

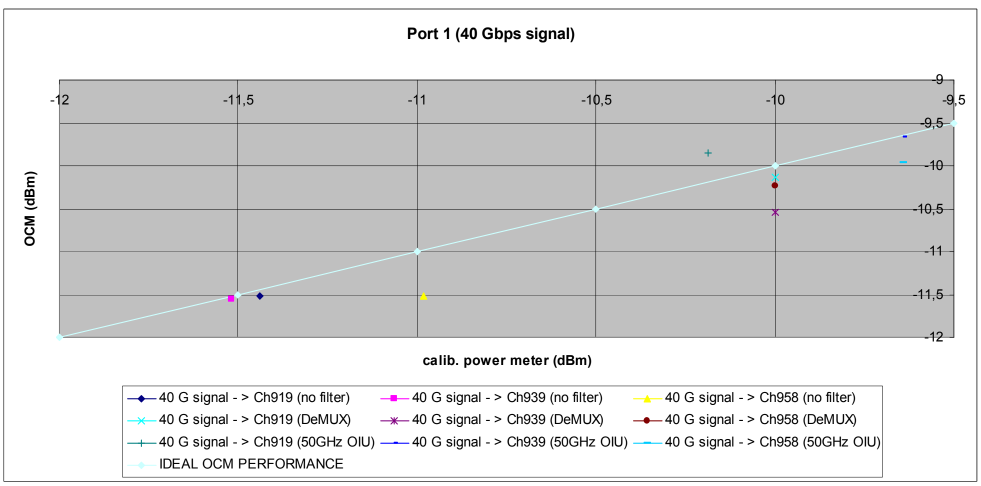


Figure 3-35: 40G signal, OCM detected power vs. calibrated power meter for different conditions

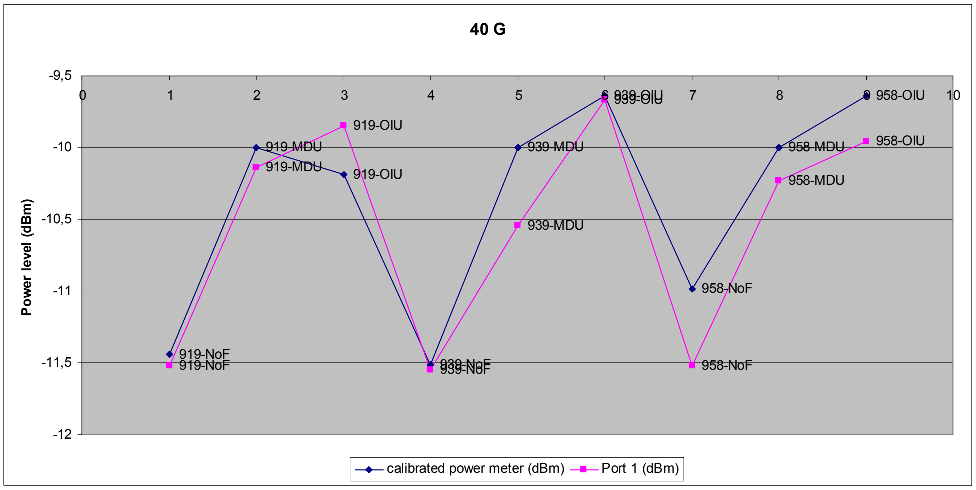


Figure 3-36: 40G signal, difference with calibrated power meter for different conditions

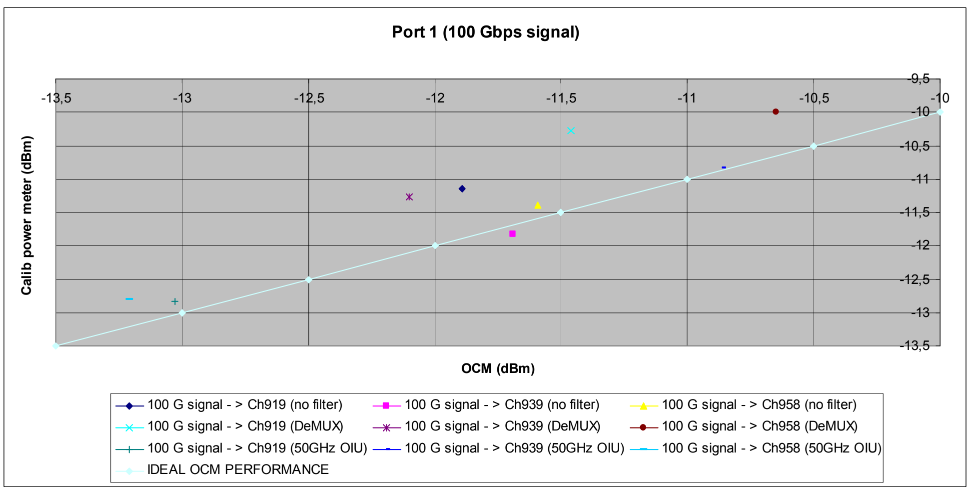


Figure 3-37: 40G signal, difference with calibrated power meter for different conditions

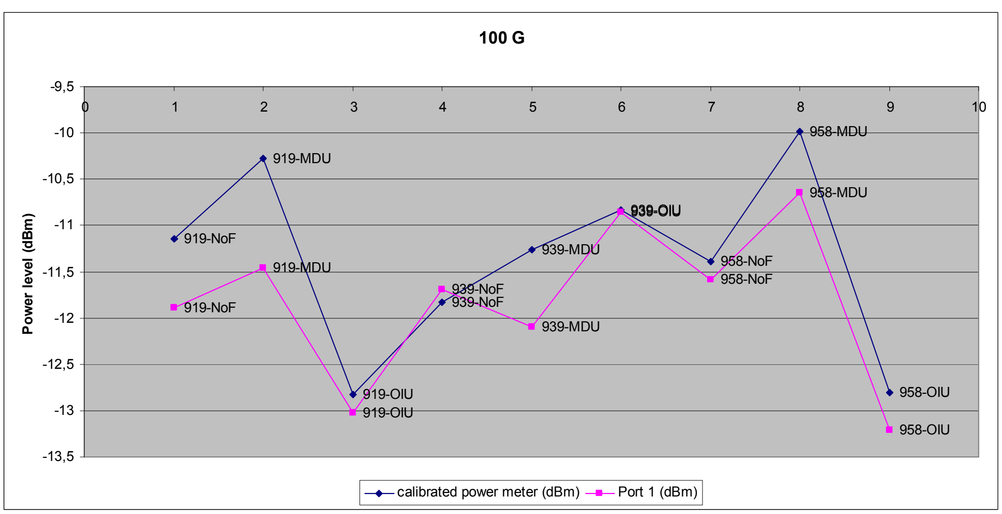


Figure 3-38: 100G signal, difference with calibrated power meter for different conditions

Based on above figures, OCM measures more precise power levels for 40 and 100 Gbps signal In comparison with 10 Gbps. The difference between the values measured by OCM and by a calibrated power meter is relatively smaller.

Minimum detectable power is a test to find the minimum power level of the input signal to the OCM for 10 Gbps, 40 Gbps and 100 Gbps by constantly decreasing the input light until the OCM is unable to detect it. Figure 3-39 shows the minimum detectable power levels for 10, 40 and 100 Gbps signals.

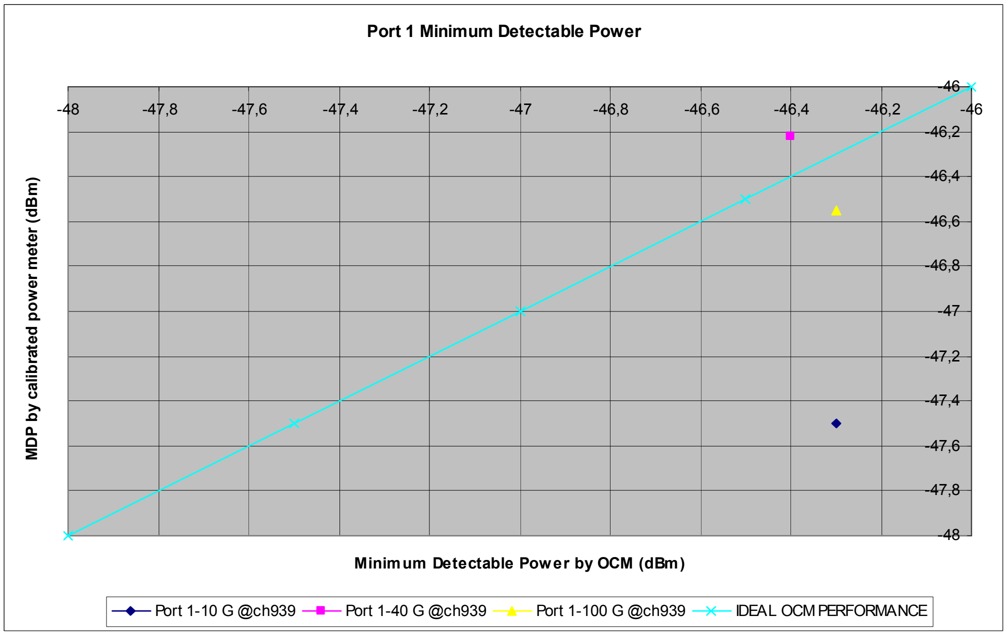
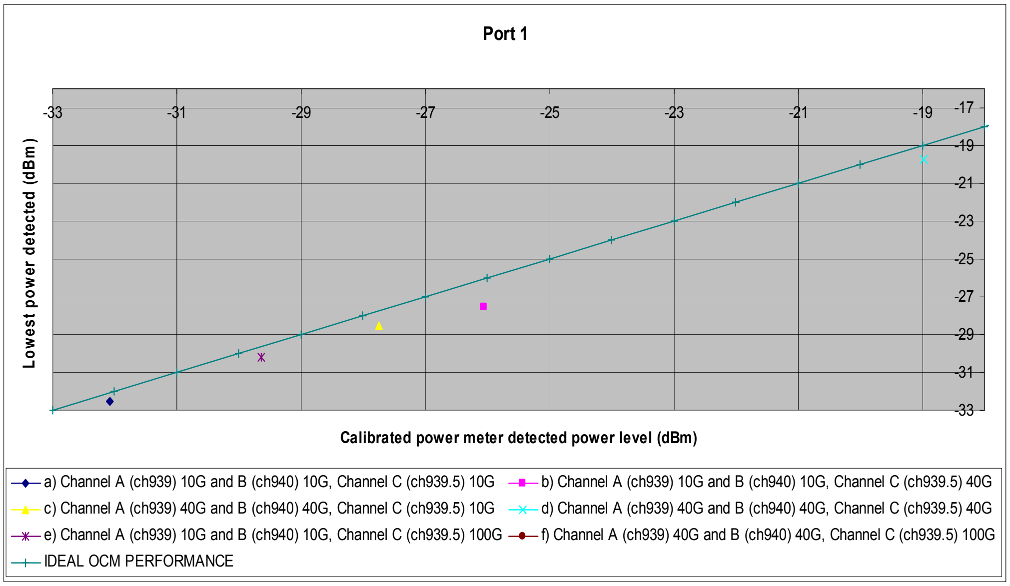


Figure 3-39: Minimum detectable power levels

Minimum detectable power for this OCM is around -47 dBm. This measurement is more precise for 40 and 100 Gbps signal since they are closer to the blue line representing ideal performance of OCM.

Adjacent channels' power effect on the center channel is studied through a test by decreasing the power level on the middle channels accompanied by two neighbors (one positioned 50GHz up on the spectrum and the other, 50 GHz lower in spectrum having same power level and same bit rate) until the OCM is unable to detect any power in the middle channel. The middle channel has varying bit rate. Figure 3-40 shows the differences.



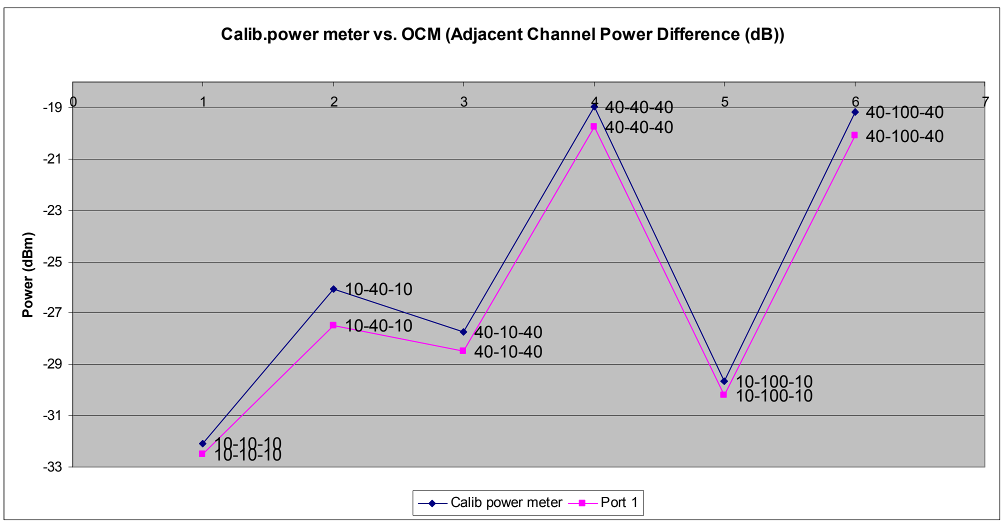


Figure 3-40: Adjacent channel power effect for 10G, 40G and 100 G

In table 2, a summary of the power levels of two neighbor channels and the middle channels along with the value detected by a calibrated power meter is provided

Ch 939 (neighbor)	Ch 939.5 (target)	Ch 940 (neighbor)	Powermeter	Target-Powermeter
-15,65 dBm (10G)	-32,5 dBm (10G)	-15,74 dBm (10G)	-32,08 dBm	0,42 dB
-15,4 dBm (10G)	-27,5 dBm (40G)	-15,2 dBm (10G)	-26,05 dBm	1,45 dB
-13,13 dBm (40G)	-28,5 dBm (10G)	-13,17 dBm (40G)	-27,75 dBm	0,75 dB
-13,1 dBm (40G)	-19,76 dBm (40G)	-13,31 dBm (40G)	-18,98 dBm	0,78 dB
-15,58 dBm (10G)	-30,2 dBm (100G)	-15,25 dBm (10G)	-29,64 dBm	0,56 dB
-13,14 dBm (40G)	-20,11 dBm (100G)	-13,16 dBm (40G)	-19,17 dBm	0,94 dB

Table 2: Power levels (dBm) for center channel measured by the company H's OCM and power meter and its neighbors

The difference between target channel's power levels with two neighbors is in range of 17 dB (for 10 Gbps signal as target) and 7 dB (for 40 Gbps signal as target). For most of the cases, the difference between the value measured by OCM and the same value measured by a calibrated power meter is less than 1 dB.

Company I

It is a single port OCM. The performance of it has been tested with the same set of methods described in the previous section. Figures 3-41 to 3-46 show the achieved results with company I's OCM for different tests.

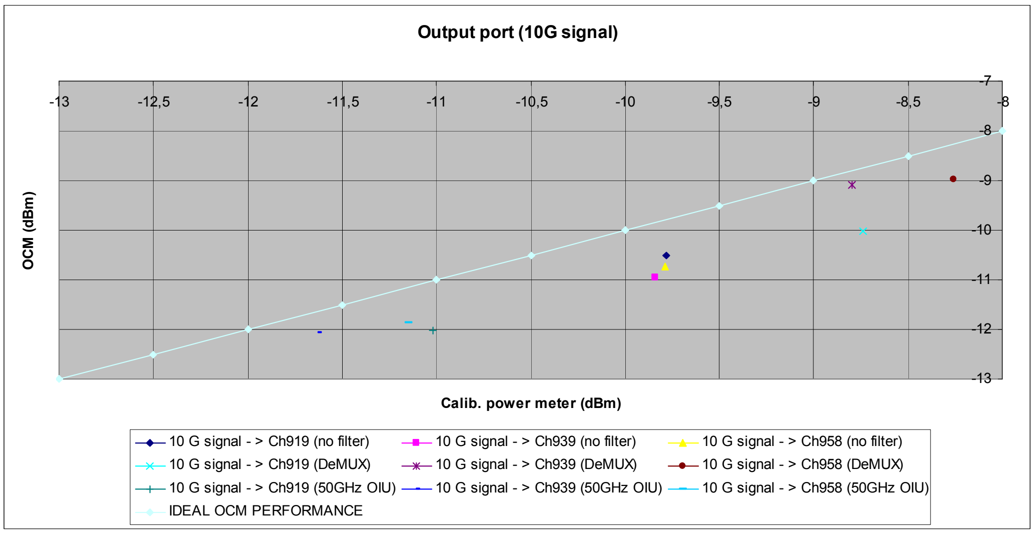


Figure 3-41: 10G signal, OCM detected power vs. calibrated power meter for different conditions

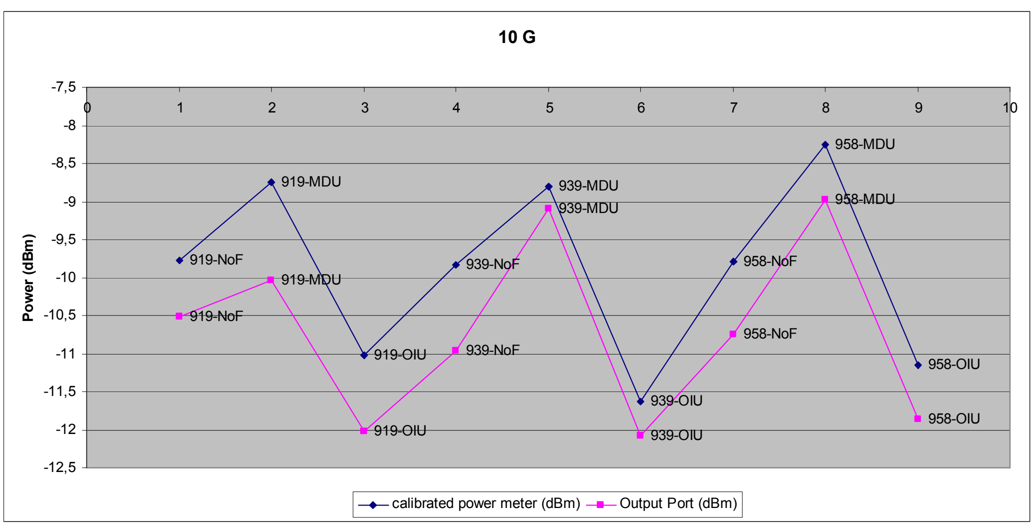


Figure 3-42: 10G signal, difference with calibrated power meter for different conditions

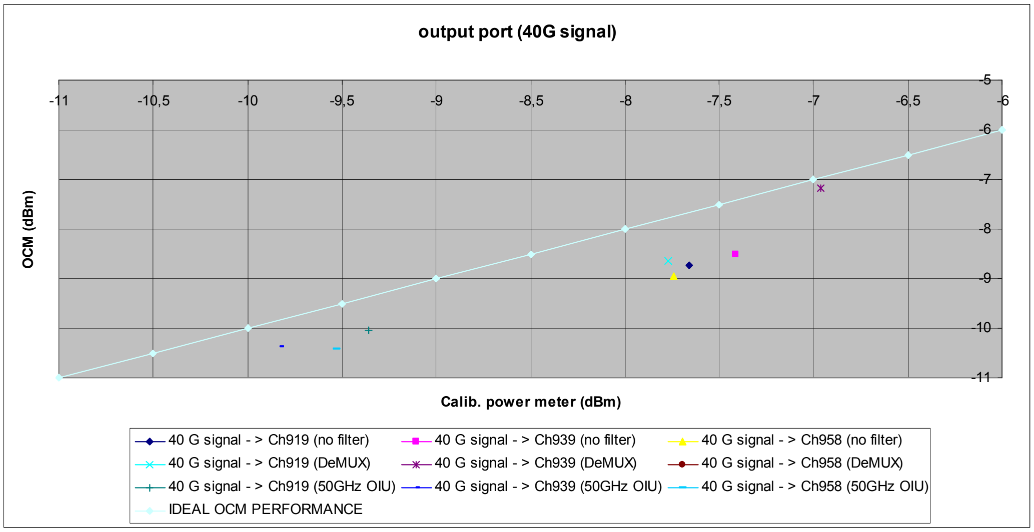


Figure 3-43: 40G signal, OCM detected power vs. calibrated power meter for different conditions

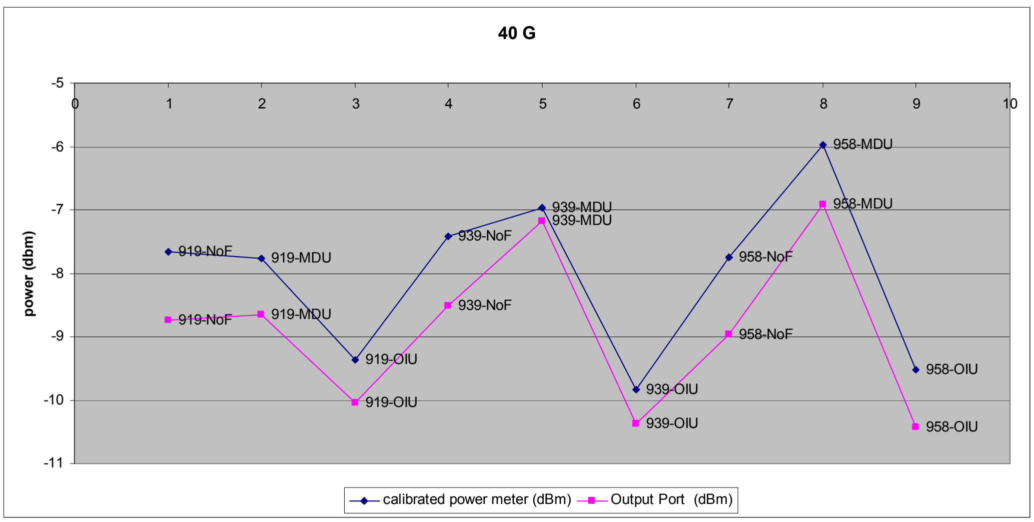


Figure 3-44: 40G signal, difference with calibrated power meter for different conditions

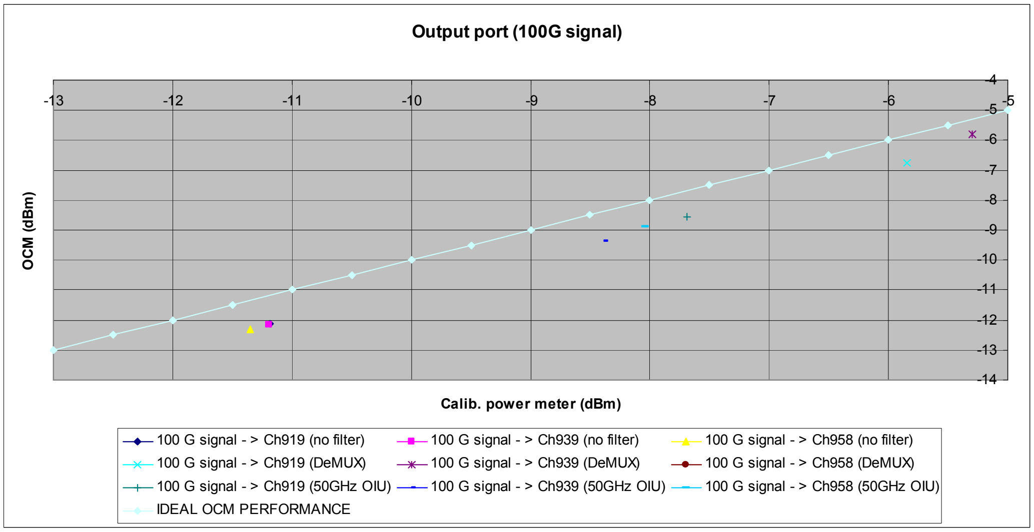


Figure 3-45: 100G signal, OCM detected power vs. calibrated power meter for different conditions

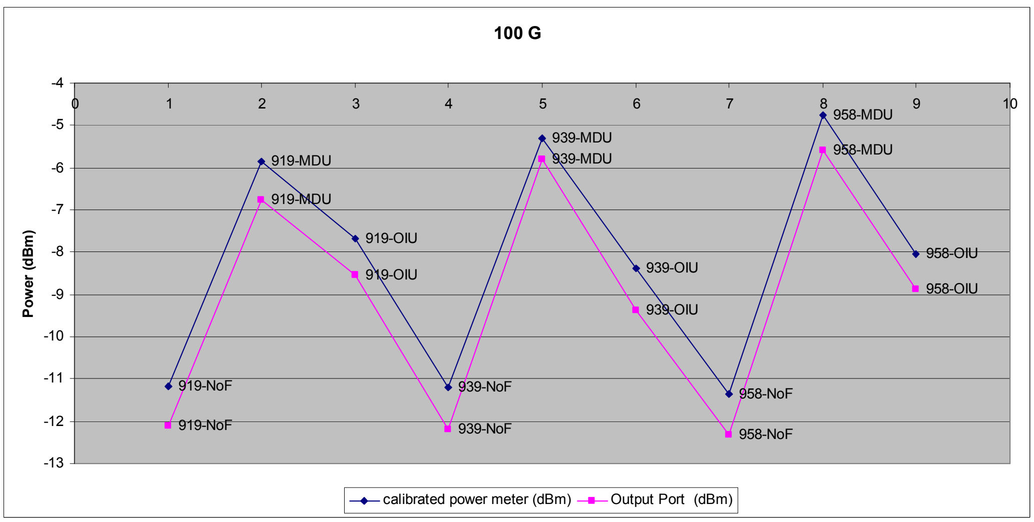


Figure 3-46: 100G signal, difference with calibrated power meter for different conditions

The difference between the value measured with OCM and the same value measured with a calibrated power meter is relatively larger compared to company H's OCM.

Minimum detectable power

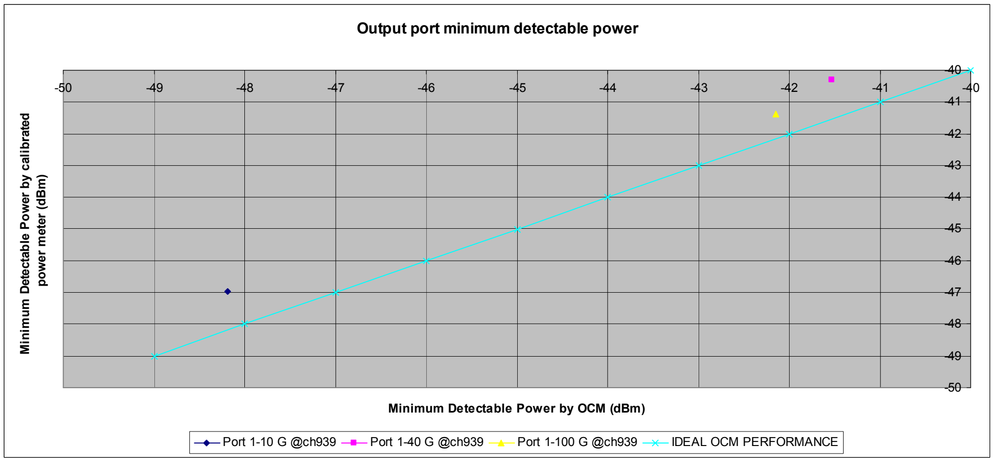


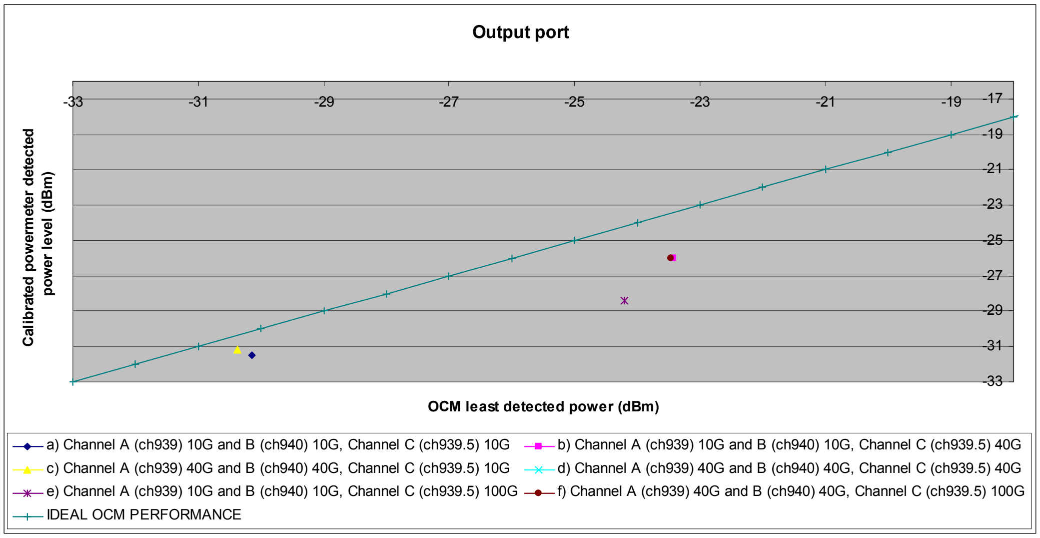
Figure 3-47: Minimum detectable power for 10G, 40G and 100G compared with a calibrated power meter

Minimum detectable power for this OCM is around -42 dBm for 40 and 100 Gbps which is obviously worse than the same results for company H's OCM.

Adjacent channels' power effect

Figure 3-48 shows the effect of adjacent channels' power level on the detection of smallest power level in target channel. Also here it can be seen that the differences are

Larger compared to company H's OCM meaning that the value detected by the OCM is not that precise.



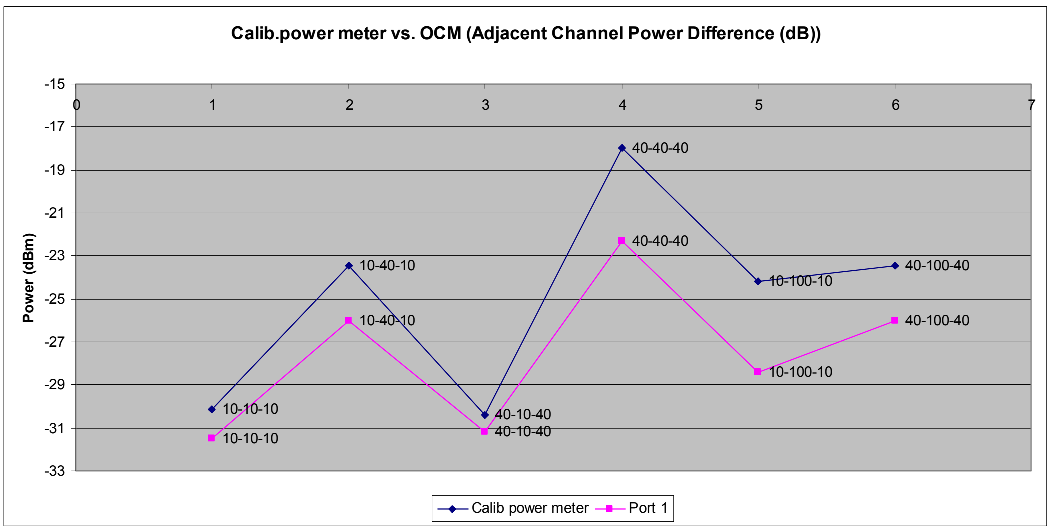


Figure 3-48: Adjacent channel power effect for 10G, 40G and 100 G

A summary of the power levels of two neighbor channels and the middle channels along with the value detected by a calibrated power meter is provided in table 3.

Ch 939 (neighbor)	Ch 939.5 (target)	Ch 940 (neighbor)	Powermeter	Target-Powermeter
-14,15 dBm (10G)	-31,47 dBm (10G)	-14,1 dBm (10G)	-30,14 dBm	1,33 dB
-14,12 dBm (10G)	-26 dBm (40G)	-14,02 dBm (10G)	-23,43 dBm	2,57 dB
-15 dBm (40G)	-31,17 dBm (10G)	-14,93 dBm (40G)	-30,37 dBm	0,8 dB
-15,69 dBm (40G)	-22,29 dBm (40G)	-15,75 dBm (40G)	-17,96 dBm	4,33 dB
-14,02 dBm (10G)	-28,43 dBm (100G)	-14,09 dBm (10G)	-24,2 dBm	4,03 dB
-15,23 dBm (40G)	-26 dBm (100G)	-15,27 dBm (40G)	-23,46 dBm	2,54 dB

Table 3: Power levels (dBm) for center channel measured by the company I's OCM and power meter and its neighbors

3.2.5 TDC performance

- **Purpose of the test**: was to evaluate the performance of TDC module in 40 Gbps system. The module is subjected to series of tests in three different ambient temperatures and two different filtering schemes (weak and strong) to verify the desired performance.
- **Test method**: setup is the same as in figure 3-49.The module is put in a heat chamber to mimic different ambient temperatures (at -5°C, 23°C and 58°C) and check the effect of temperature change on the performance of TDC module input signal to the TDC module was chosen to be 5 dBm. Filtering scheme was weak (a Mux and Demux having bandwidth approximately equal to 75 GHz) and strong (A Mux and Demux and 2 OIUs having a bandwidth approximately equal to 45 GHz) exhibiting the effect of filtering on the compensation at high dispersion levels (both positive and negative).To create a negative dispersion along the link, a single mode fiber optic with length of 40 Km was used and for positive dispersion a dispersion compensating fiber with the same length.

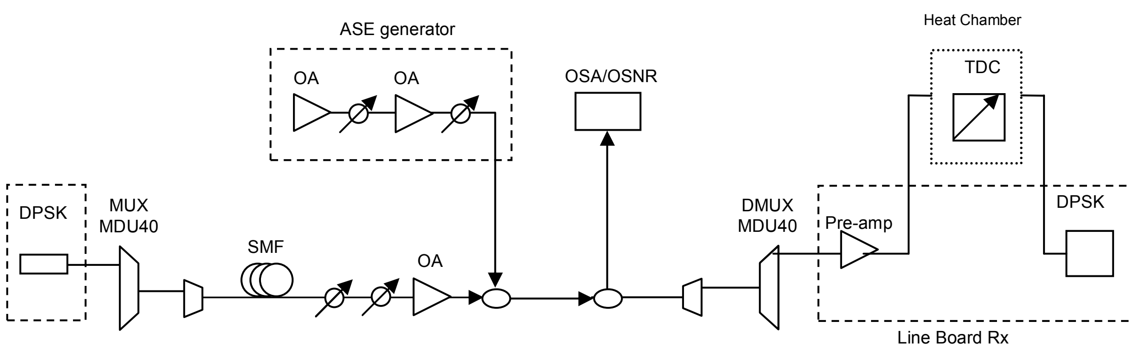


Figure 3-49: Measurement setup for company K's TDC

- **Target parameter**: to evaluate the ability to compensate for a range of dispersion (from 0 ps/nm.Km up to ±700 ps/nm.Km) with the two different filtration schemes.
- **Outcomes:**

OSNR levels are measured for each dispersion value between -700 to +700 ps/nm.Km. Input power to the DPSK module can be changed using an amplifier positioned before the TDC module to find the optimum input power. The result for the both filtering schemes (weak and strong) and three different temperatures are presented in figures 3-50 to 3-52.

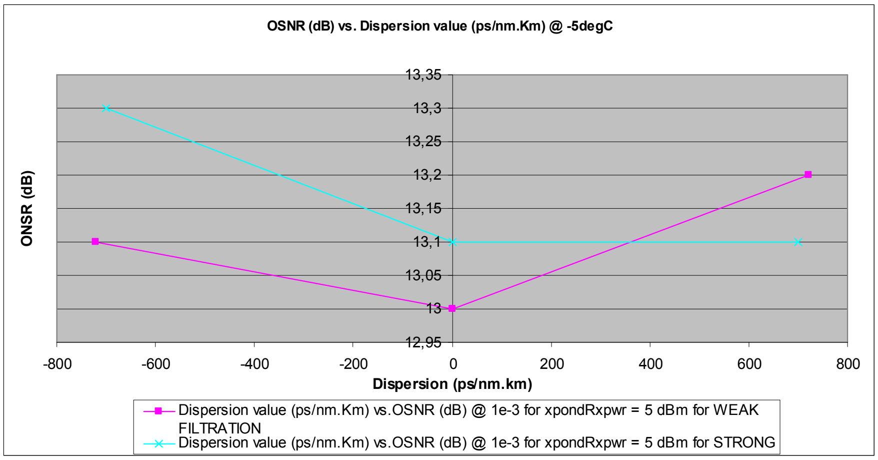


Figure 3-50: OSNR vs. dispersion value for weak and strong filtration at -5° C

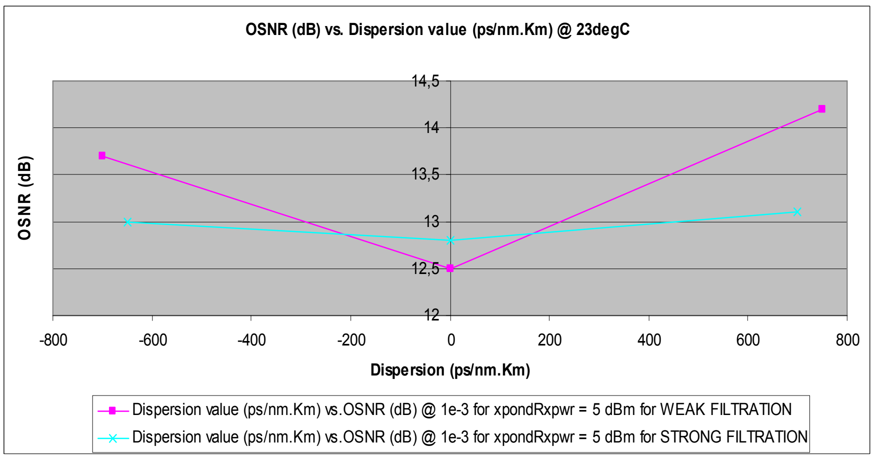


Figure 3-51: OSNR vs. dispersion value for weak and strong filtration at 23° C

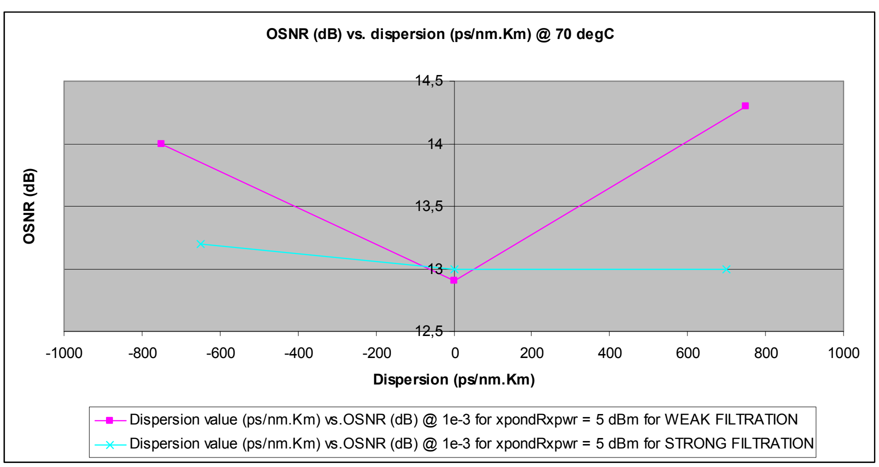


Figure 3-52: OSNR vs. dispersion value for weak and strong filtration at 70°C

Weak filtration has lower OSNR level for all three temperature settings at 0 ps/nm.Km dispersion value but as dispersion increases in both positive and negative axis, strong filtration shows lower OSNR level. As figure 3-53 demonstrates, this is because at 0 ps/nm dispersion, significant part of the signal is wide band (~48 GHz) so cutting a part of it with filter (strong filtration) leads to degradation of OSNR while weak filtration can let through almost entire signal bandwidth unaltered (the difference between weak and strong filtration OSNR levels at 0 ps/nm is not that large since strong filtration has a bandwidth of about 45 GHz). At high dispersions, significant part of the signal is much narrower (~38 GHz) so filtration leads to better OSNR.

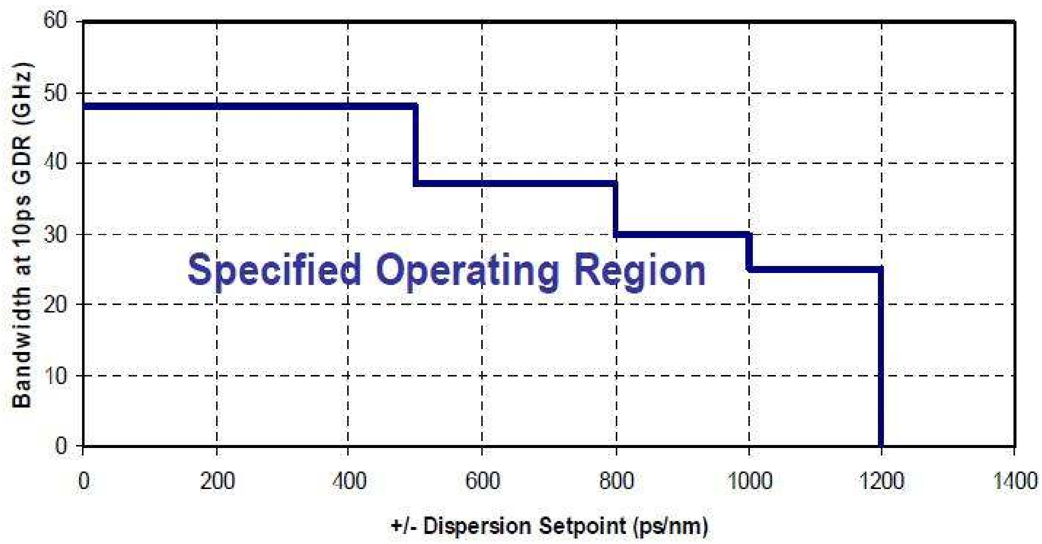


Figure 3-53: Operating bandwidth for different dispersion settings at 10 ps Group Delay Ripple

3.3 Guidelines for upgrade

Based on the results achieved from the tests discussed in previous section, a number of suggestions and guidelines for migrating from 10 Gbps to 40 Gbps and 100 Gbps signals (and even coexistence of 10 Gbps signal with either of them) are derived from the results:

3.3.1 BER versus OSNR for 40 G and 100 G

10-40-10: according to figures 3-12 to 3-14, having a single channels at 40 Gbps and 3,5 dBm of launch power would have the lowest OSNR (13,5 dB) at reference BER for with FEC (1.00E-4). By adding 2 neighbor channels containing 10 Gbps and with 200 GHz spacing with center channels, a penalty of 0,4 dB is added to the OSNR. This penalty is because of nonlinear effects imposed to center 40 Gbps signal by two 10 Gbps neighbors. By increasing the launch power to 6,5, OSNR tends to increase to 14,2 dB. Higher launch power means stronger effects of nonlinearities and this is the reason why one sees higher OSNR at higher launch powers. This trend continues by launching 9,5 dBm that has OSNR of 14,5 and a nonlinear effect penalty (adding two 10Gbps neighbors) of 0,4 dB.

By decreasing the spacing from 200 GHz to 100 GHz, OSNR of 3 dBm launch power increases to 14 dB but the penalty drops to >0,1 dB for all the higher launch power. This is because here the dominant effect is nonlinear effects triggered by 40 Gbps signal's high launch power.

By decreasing the separation even more to 50 GHz, a strange phenomenon happens and that is 40 Gbps single channel signal, with either high or low launch power, has lower OSNR than the case being accompanied by two 10 Gbps.

10-100-10: according to figures 3-15 to 3-17, lowest OSNR is again for single channel 100 Gbps signal at 13,5 dB and then comes 3,5 dBm with two 10 Gbps neighbors with a small penalty to previous one at around 13,6 (extrapolated). In tighter spacing, the lowest OSNR belongs to lower launch power and then the same power with neighbors. Also the penalty between two (without and with neighbors) increases as the launch powers increase.

40-100-40: According to figures 3-18 to 3-20, the above mentioned trend is sharply pronounced in this case

Conclusion: at tighter spacing (50 GHz spacing which is the target spacing for 40 Gbps and 100 Gbps DWDM) lower launch power has always lower OSNR (because of smaller nonlinear effects from neighbors plus from the target signal itself).But when having broadband signals such as 40 Gbps and 100 Gbps both at target and as two neighbors) the interference increases which results in degradation of OSNR. At very low launch power, the dominant unwanted effect is ASE noise from amplifiers.

3.3.2 The effects of filtering on 40 Gbps and 100 Gbps signals

Based on figure 3-23 and 3-24 with tighter filters (narrower bandwidth) one can understand that the signal spectrum becomes narrower. The order could be like this (larger bandwidth>…>smaller bandwidth):

MDU > OIU > WSS > any combination of MDU, OIU, WSS > wavelengthBlocker

The smallest possible bandwidth for 100 Gbps signal is 30 GHz .Tighter filtering than 30 GHz leads to signal loss by the receiver.

Although it could be thought that tight filtering in general is not desirable (because of cutting the significant part of the signal) but in some cases (like using the TDC) it is beneficial to have a tighter signal for better compensation of dispersion at high dispersion settings.

3.3.3 The effects of filtering on BER versus OSNR

Figure 3-29 shows that tight filtering imposes a penalty of around 2 dB for 40 Gbps but it is less than 1 dB for 100 Gbps. This is because 40 Gbps signal has wider spectrum than 100 Gbps. The highest penalty is for the wavelengthBlocker that has 30 GHz bandwidth.

There is very small BER penalty for 100 Gbps signal when its bandwidth is decreases from 46 GHz to 30 GHz (loss of signal limit).

3.3.4 OCM performance

According to figures 3-33 to 3-40, company H's OCM has the best results among the other two (although company G is the current OCM that Transmode supplies for its customers) because of:

- Has four ports
- Supports 10, 40 and 100 Gbps (while for example, company G and I don't)
- Has lower minimum detectable power (~46 dBm)
- The offset between OCM detected power and a calibrated power meter is constant (around 1 dB) which can be easily compensated and have a precise performance
- Fulfils Transmode's requirement for the minimum margin between neighbors for 10 Gbps and 40 Gbps (minimum 17 dB between 10 Gbps and its neighbors and minimum 7 dB between 40 Gbps and its neighbors)

3.3.5 TDC performance

With regard to figure 3-50 to 3-52, at zero dispersion, weak filtration has lower OSNR because the entire signal passes and nothing is cut. At high dispersion (both + and – dispersions) the signal spectrum is smaller and therefore strong filtration has lower OSNR.

3.4 Future works

It seems necessary to perform more tests and measurements on

- PMD compensator for 40 Gbps
- the effect of the other forms of transceivers (like QSFP+) in 40 Gbps and 100 Gbps
- the possible effect of different manufacturing technology in the equipments that have been tested in this report

Also, based on the results that are presented in this report, it is beneficial to carry out test on the equipments and methods tested in the report but with optimized and more educated test conditions (such as input power, temperature, setup and etc.)

4 References

[1] Ildefonso M. Polo, “Optical Modulation for High Bit Rate Transport Technologies”, Sunrise Telecom, Oct 2009

[2] Dirk van den Borne, “Robust Optical Transmission Systems: Modulation and Equalization”, Eindhoven : Technische Universiteit Eindhoven, 2008. ISBN 978-90-386-1794-7

[3] Javier Cano Adalid, “Modulation Format Conversion in Future Optical Networks”, Research Center COM -Technical University of Denmark, March, 2009

[4] Govind.P.Agrawal, Lightwave Technology: Telecommunication Systems, Wiley-Interscience, Dec 2006

[5] ITU-T recommendation G.707/Y.1322 (12/2003)

[6] IEEE standard 802.3ae

[7] ITU recommendation G.709/Y.1331 (12/2009)

[8] B. Collings, F. Heismann,G. Lietaert, Reference Guide to Fiber Optic Testing, volume2:Advanced Fiber Optic Testing, JDS Uniphase Corporation,2009

[9] S. Ten, M. Edwards,”An introduction to the fundamentals of PMD in fibers”,Corning-WP5051, Jul 2006

[10] S. P. Singh, N. Singh “Nonlinear effects in optical fibers: origin, management and applications” Progress In Electromagnetics Research, PIER 73, 249–275, 2007

[11] Avid Lemus, “Optical Digital Communications :Technology & Modulation Formats”, Stratalight communications, Oct 2008

[12] ITU-T recommendation G.652

[13] P.J.Winzer, R.J. Essiambre, “Advanced Optical Modulation Formats”, Proceedings of the IEEE | Vol. 94, No. 5, May 2006

[14] A.H. Gnauck, P.J. Winzer, “Optical Phase-Shift-Keyed Transmission” Journal of Light wave Technology, vol. 23, no. 1, Jan 2005

[15] R. Vaez-Ghaemi, “Next Generation Optical Transport Networks”, JDS uniphase

[16] H.Åhlfeldt, “Evaluation Scope 40 Gbps DPSK system”, Transmode’s internal, 2011

[17] 40G Transmission in Metro and Long-Haul Networks, ECI white paper

[18] R. J. Essiambre, B. Mikkelsen, and G. Raybon, “Intra-channel crossphase modulation and four-wave mixing in high-speed TDM systems,” Electron. Lett., vol. 35, no. 19, pp. 1576–1578, 1999.

[19] X.Liu, “Nonlinear effects in phase shift keyed transmission”, Optical Fiber Communication Conference, 2004. OFC 2004

[20] B. Vasic, I. B. Djordjevic,V. S. Rao, “Suppression of intrachannel nonlinearities using BCJR algorithm and iterative decoding”,Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference. OFC 2006

[21] E.Pincemin, J.Karaki, Y.Loussouarn, H.Poignant, C.Betoule ,G.Thouenon, R.Le Bidan, "Challenges of 40/100 Gbps and higher-rate deployments over long-haul transport networks" Optical Fiber Technology 17 (2011) 335–362

[22] K.Wani, T.Ono, "40 Gb/s Dense Wavelength Division Multiplexing Transmission System", Fujitsu Sci. Tech. J., vol. 45, no. 4, pp. 371-376, Oct 2009

[23] M.Birk, B.Mikkelsen, "40/100 Gb/s Transmission Systems, Design and Design Trade-offs" OFCNFOEC 2010

[24] Ross Saunders, "Coherent DWDM technology for high speed optical communications", Optical Fiber Technology 17 (2011) 445–451

[25] J.Anderson, M.Traverso, "Optical Transceivers for 100 Gigabit Ethernet and its Transport", IEEE Communications Magazine , March 2010

[26] Optical Internetworking Forum (OIF), "Implementation Agreement for Integrated Polarization Multiplexed Quadrature Modulated Transmitters", document no. IA # OIF-PMQ-TX-01.0,Mar 2010

[27] Optical Internetworking Forum (OIF), "Implementation Agreement for Integrated Dual Polarization Intradyne Coherent Receivers", document no. IA # OIF-DPC-RX-01.0, Apr 2010

[28] Y.H. Wang, I. Lyubomirsky, "Impact of DP-QPSK Pulse Shape in Nonlinear 100 G Transmission", Journal of Lightwave Technology, vol. 28, no. 18, Sep 15, 2010

[29] C.Xie, "WDM coherent PDM-QPSK systems with and without inline optical dispersion compensation", Optics Express 4815, vol. 17, No. 6 , Mar 2009

[30] G.Raybon, P.J.Winzer, "100 Gbps challenges and solutions", OFC/NFOEC 2008-OTuG1

[31] R.Saunders, G.Nicholl, K.Wollenweber,T.Schmidt, "Can 100Gb/s wavelengths be deployed using 10Gb/s engineering rules?", Optical Transmission Systems and Equipment for Networking VI. Edited by Weiershausen, Werner; Dingel, Benjamin B.; Dutta, Achyut K.; Sato, Ken-ichi. Proceedings of the SPIE, Volume 6774, pp. 67740B (2007)

[32] M.Mussolin, M.Forzati, J.Mårtensson, A.Carena, G.Bosco, "DSP-based compensation of non-linear impairments in 100 Gb/s PolMux QPSK", Transparent Optical Networks (ICTON), 2010 12th International Conference on,2010 E-ISBN : 978-1-4244-7797-5

[33] S. J. Savory, "Compensation of Fibre Impairments in Digital Coherent Systems", ECOC 2008, 21-25 September 2008, Brussels, Belgium

[34] S. J. Savory, "Digital filters for coherent optical receivers", Optics Express 804, vol. 16, No. 2, Jan 2008

[35] Fujitsu white paper,"The path to 100 G",2011

[36] C.F.Lam, W.I.Way, "A system's view of metro and regional optical networks", Proceedings Vol. 7235,Optical Metro Networks and Short-Haul Systems, Werner Weiershausen; Benjamin B. Dingel; Achyut K. Dutta; Atul K. Srivastava, Editors, 723503

[37] SFF Committee, "10 Gigabit Small Form Factor Pluggable Module", Revision 4.5 Aug 2005-INF-8077i

[38] Matt Traverso, "CFP MSA Hardware Specification", Revision 1.4, Jun 2010

[39] K. Yu, D.Lee,O.Solgaard, " Variable Bandwidth Optical Filters with Vertical Micromirrors and Silicon Optical Bench Alignment Technology", Lasers and Electro-Optics Society, 2004. LEOS 2004. The 17th Annual Meeting of the IEEE,ISBN 0-7803-8557-8

[40] X.Shu,K.Sugden, P.Rhead, J.Mitchell, I.Felmeri, G.Lloyd,K.Byron, Z.Huang, I.Khrushchev,I.Bennion, "Tunable Dispersion Compensator Based on Distributed Gires–Tournois Etalons", IEEE Photonics Technology Letters, vol. 15, no. 8, Aug 2003

5 Appendices

5.1 Appendix 1: Data sheets

5.1.1 XFP

- **Company A**:

PRODUCT FEATURES

- Supports 8.5Gb/s to 11.35Gb/s
- -800 to +800 ps/nm Dispersion Tolerance
- Supports 50GHz ITU-based channel spacing (C-Band) with a wavelength locker
- Monolithic MZM Tunable TOSA
- Temperature range: -5°C to 70°C
- RoHS-6 Compliant (lead-free)
- Power dissipation <3.5W
- Built-in digital diagnostic functions
- High performance PIN Receiver
- Adjustable receiver threshold with option for automatic optimization through FEC feedback

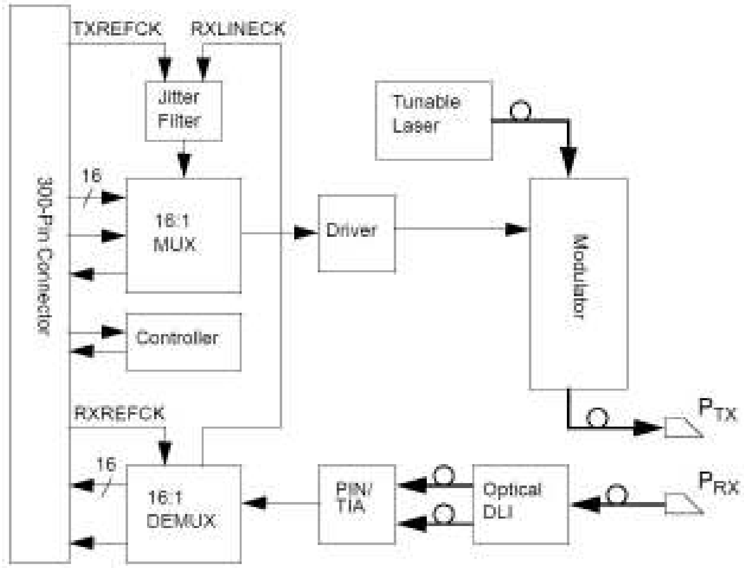
APPLICATIONS

- DWDM 10Gb/s SONET/SDH
- DWDM 10Gb/s Ethernet & 10Gb/s Fibre Channel
- DWDM 10Gb/s SONET/SDH w/FEC
- DWDM 10Gb/s Ethernet and 10Gb/s Fibre Channel w/FEC

Company A produces the XFP transceivers used in the mentioned test to transmit and receive a 10 Gbps signal required for some tests. Beside 8G FC, it can support 10 GbE LAN/WAN PHY. It has a MZ modulator in the transmitter and a PIN receiver. It also can tolerate dispersions in the range of ±40 Km.

5.1.2 300-pin transceiver

- **Company O**:



Company O suggest this block diagram schematic to show the inside building blocks of a 300-pin transceiver. It consists of a connector that is connected to both the transmitter and receiver parts. Transmitter part has a tunable laser that is modulated by a driver that is fed with the output of a 16:1 mux and the generated signal is sent from the output of the modulator. At the receiver side, the signal is detected by a PIN and fed to a 16:1 demux unit.

5.2 Multiplexer/Demultilexer

- **Company B**:

Mux/Demux unit used in the tests that were carried out in this report are an Athermal Arrayed Waveguide Grating which has a 40 channels each having a 100 GHz of spacing between each other.

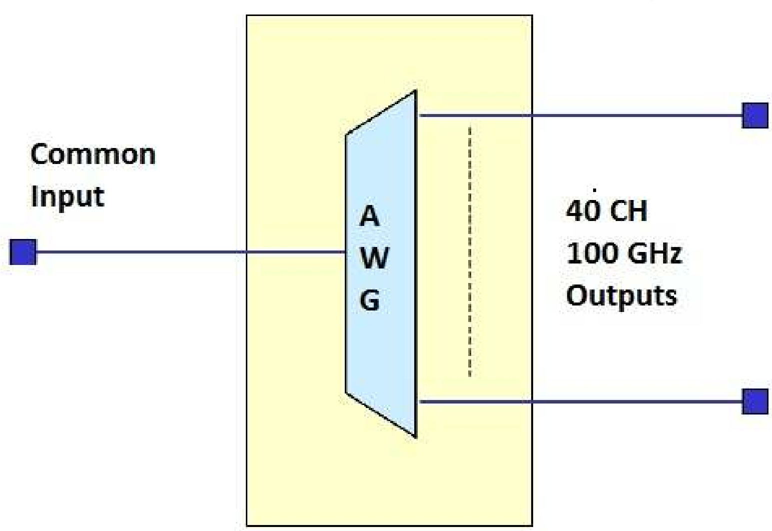
40-Channel 100GHz Athermal AWG

Athermal AWG (Arrayed Waveguide Grating) is a high-performance DWDM mux/demux device operating on 100GHz channel spacing without the need for temperature stabilization. The PhotonIC™ planar processed silica-on-silicon chips comprise arrayed channel waveguides to separate or combine multiple wavelengths. Athermal AWGs allow multiplexing and demultiplexing of DWDM signals over a wide operating temperature range, without the need for heater drive and monitoring elec- tronics. These AWGs offer low insertion loss, excellent channel isolation, ease of fiber handling, and long-term reliability in a compact package. Gemfire's athermalization techology simplifies deployment of AWG multiplexers/ demultiplexers by DWDM network providers.

KEY FEATURES:

- 40 Channels x 100GHz Mux/Demux
- 44 Channel Option Available
- Gaussian and Wide Passbands
- Fully Passive Module
- Wide Operating Temperature Range
- Low Insertion Loss and PDL
- Low Crosstalk
- High Uniformity
- No Electronics Required
- Compact Footprint
- Versatile Alternative to TFF Mux
- Telcordia GR-1209/GR-1221 Qualified

Functional Schematic Diagram



5.3 Wavelength blocker

- **Company C**:

It has a 8 channel wavelength blocker plus an OCM unit to measure the power levels. The spacing is 50 GHz with a channel passband of ±12,5 GHz

This document serves as an operational specification for the 50 GHz FULL FLEDGE "Wavelength Blocker" Array Module. The module includes 8 fully independent 1x1 wavelength blockers, each of which is capable of routing, attenuating or blocking channels on that specific optical path. One additional port is configured as an Optical Channel Monitor (OCM). The device is capable of operating as a programmable spectrum device with alternate channel plans that are defined by the user.

4.1 Waveblocker Performance

Optical BOL specifications over operating temperature are detailed in the following table.

Parameter	Path	Min	Typ	Max	units	Comments
Channel Spacing	all		50		GHz	
Channel Range	all	191.30		196.05	THz	96 channels
Channel Passband	all		±12.5		GHz	
Insertion Loss (IL)	Wnl - WnX	2.5	4	6	dB	
Return Loss	all			40	dB	
Directivity	Any 2 ports			40	dB	
WDL	all		1.0	2.0	dB	
PDL	all		0.35	0.50	dB	VOA < 5 dB
PDL	all			0.70	dB	5.1 dB < VOA <10 dB
PDL	all			0.85	dB	10.1 dB < VOA <15 dB
-1.0 dB Passband	all	±12.5	±17.5		GHz	
-3.0 dB Passband	all	±17.5	±20		GHz	
-30 dB Stopband	all	±10	±15		GHz	
Average Channel Isolation (ACI)	All	-35			dB	Minimum channel isolation measured over any passband
Chromatic Dispersion	all	-10		10	ps/nm	
Group Delay Ripple	all			1.0	ps	
DGD (PMD)	all		0.15	0.5	ps	
Multipath Interference	all	40			dB	within Channel Passband
Switch Block Isolation	all	40			dB	Power on w/opaque command
		40			dB	In power off state
VOA Range		15			dB	
VOA Setpoint Resolution				0.3	dB	VOA < 10 dB
				0.5	dB	10 dB < VOA < 15 dB
VOA Repeatability				±0.4	dB	VOA < 10 dB
				±0.7	dB	10 dB < VOA <15 dB
VOA Accuracy				±0.6	dB	VOA < 5 dB
				±0.8	dB	5.1 dB < VOA <10 dB
				±1.2	dB	10.1 dB < VOA <15 dB
Optical Power Limit	any			27	dBm	Entire input spectrum
Optical Power Limit	any			15	dBm	1 channel (power in passband)
Switching Time[1]	any	5		30	ms	90/10 Transition Time
Attenuation Change[1]	any	5		30	ms	any VOA change <= 1 dB

[1] For a single channel configuration change

5.4 Optical Interleaver Unit (OIU)

- **Company D**:

This specification clarifies the technical optical characteristics of the Optical Interleaver Unit used throughout the test. The spacing between the input channels is 100 GHz and it supports ITU channel grid between 192000 GHz up to 196000 GHz.

Performance Specification

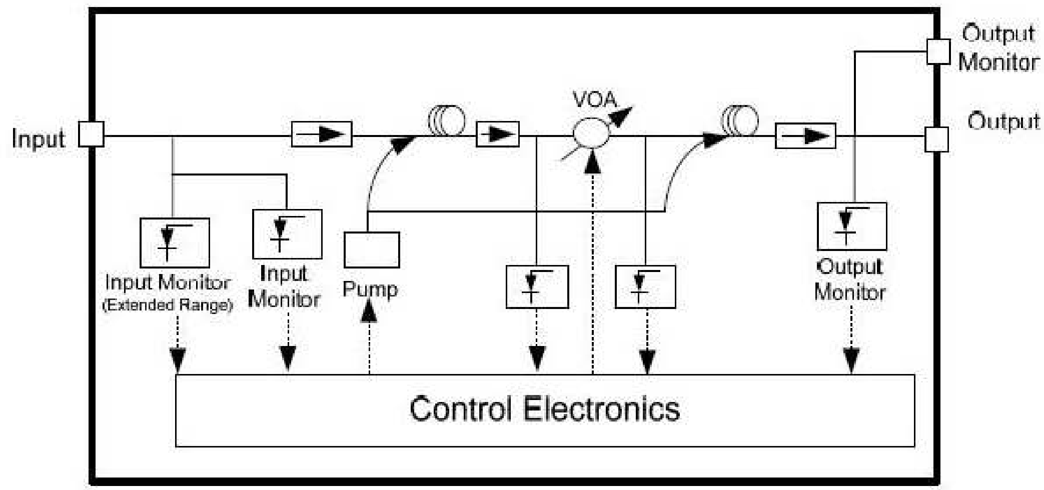
	Min	Typioal	Max	Unit
Center Wavelength Range	1529.55		1561.42	nm
Center Frequency Range	192000		196000	GHz
Channel Center Wavelength		ITU Grid		
Input Channel Spacing		50		GHz
Output Channel Spacing		100		GHz
Clear Bandwidth		± 8		GHz
Insertion Loss [1)]		1.0	1.8	dB
Ripple		0.2	0.3	dB
Insertion Loss Uniformity		0.2	0.4	dB
Adjacent Channel Isolation	22			dB
Polarization Dependent Loss (PDL)		0.2	0.3	dB
Polarization Mode Dispersion (PMD)		0.2	0.3	ps
Chromatic Dispersion	- 30			ps/nm
Return Loss	45	50		dB
Directivity	50	55		dB
Operating Power Handling			24	dBm
Operating Temperature		0 to +65		°C
Storage Temperature		-40 to +85		°C
Fiber Type		Corning SMF-28		
Package Dimensions [3)]		100.5 (L) x 60.0 (W) x10.3 (H)		mm

Note:
[1] The maximum IL is under all states of polarization and within the full operating temperature and wave-length ranges specified.
[2] All spec excluding connectors
[3] The mechanical tolerance should be +/-0.2mm on all package dimensions unless otherwise custom specified.

5.5 Optical Amplifier (EDFA)

- **Company E**:

Amplifier Block Diagram



Optical Specifications

Parameters		Min	Typ	Max	Unit	Notes
Minimum Wavelength range in vacuum (C-Band)		1529		1565	nm	
Input Power - two separate ranges	With transient suppression	-27		9.5	dBm	
	Monitoring only	-38		-27	dBm	The lower 3dB range has detection accuracy of +/- 1dB
Saturated output power		19.5			dBm	For single-channel minimum is 18.5dBm.
Minimum output power		-8			dBm	For strong pump (660mW) output power is limited to -8dBm

Erbium Doped Fiber Amplifies device building block diagram is as illustrated in the above figure. It consists of number of fiber spans that are amplified by a pumping unit that has the role of amplification of the input signal. The power level of the out put can be tuned by help of a variable optical attenuator. There is a monitoring port to check on the output of the EDFA. It can amplify opical signals in the range between 1529 nm to 1565 nm. The saturated output power is 19,5 dBm.

5.6 Dispersion Compensating Module

- **Compnay J**:

The following table gives the nominal fiber length in the corresponding operating wavelength region in the C band in which chromatic dispersion is compensated by the DCM made by company J.

3.2 Dispersion

The following table defines the dispersion characteristics of the

Nominal Compensation Length [km]	Dispersion BOL RT [ps/nm]								
	1528 nm			1550 nm			1565 nm		
	min	typical	max	min	typical	max	min	typical	max
5	-80.6	-79	-76.6	-87.0	-85	-83.0	-91.4	-90	-87.4
10	-160.2	-157	-154.2	-173.0	-171	-167.0	-181.7	-179	-175.7
15	-240.4	-236	-231.4	-259.5	-256	-250.5	-272.6	-269	-263.6
20	-320.5	-314	-308.5	-346.0	-341	-334.0	-363.4	-358	-351.4
25	-400.6	-393	-385.6	-432.5	-427	-417.5	-454.3	-448	-439.3
30	-480.7	-471	-462.7	-519.0	-512	-501.0	-545.1	-537	-527.1
35	-560.8	-550	-539.8	-605.5	-597	-584.5	-636.0	-627	-615.0
40	-641.0	-628	-617.0	-692.0	-683	-668.0	-726.8	-716	-702.8
45	-721.1	-707	-694.1	-778.5	-768	-751.5	-817.7	-806	-790.7
50	-801.2	-785	-771.2	-865.0	-853	-835.0	-908.5	-895	-878.5
60	-961.4	-943	-925.4	-1038.0	-1024	-1002.0	-1090.2	-1074	-1054.2
70	-1121.7	-1100	-1079.7	-1211.0	-1195	-1169.0	-1271.9	-1253	-1229.9
80	-1281.9	-1257	-1233.9	-1384.0	-1366	-1336.0	-1453.6	-1432	-1405.6
90	-1442.2	-1414	-1388.2	-1557.0	-1536	-1503.0	-1635.3	-1611	-1581.3
100	-1602.4	-1571	-1542.4	-1730.0	-1707	-1670.0	-1817.0	-1790	-1757.0
110	-1762.6	-1728	-1696.6	-1903.0	-1878	-1837.0	-1998.7	-1969	-1932.7
120	-1922.9	-1885	-1850.9	-2076.0	-2048	-2004.0	-2180.4	-2148	-2108.4
130	-2083.1	-2042	-2005.1	-2249.0	-2219	-2171.0	-2362.1	-2327	-2284.1
140	-2243.4	-2199	-2159.4	-2422.0	-2390	-2338.0	-2543.8	-2506	-2459.8
150	-2403.6	-2356	-2313.6	-2595.0	-2560	-2505.0	-2725.5	-2685	-2635.5

Nominal Compensation Length [km]	Dispersion EOL over temperature [ps/nm]					
	1528 nm		1550 nm		1565 nm	
	min	max	min	max	min	max
5	-80.9	-76.4	-87.3	-82.8	-91.6	-87.1
10	-160.7	-153.7	-173.5	-166.5	-182.2	-175.2
15	-241.1	-230.6	-260.3	-249.8	-273.3	-262.8
20	-321.5	-307.5	-347.0	-333.0	-364.4	-350.4
25	-401.9	-384.4	-433.8	-416.3	-455.5	-438.0
30	-482.2	-461.2	-520.5	-499.5	-546.6	-525.6
35	-562.6	-538.1	-607.3	-582.8	-637.7	-613.2
40	-643.0	-615.0	-694.0	-666.0	-728.8	-700.8
45	-723.3	-691.8	-780.8	-749.3	-819.9	-788.4
50	-803.7	-768.7	-867.5	-832.5	-911.0	-876.0
60	-964.4	-922.4	-1041.0	-999.0	-1093.2	-1051.2
70	-1125.2	-1076.2	-1214.5	-1165.5	-1275.4	-1226.4
80	-1285.9	-1229.9	-1388.0	-1332.0	-1457.6	-1401.6
90	-1446.7	-1383.7	-1561.5	-1498.5	-1639.8	-1576.8
100	-1607.4	-1537.4	-1735.0	-1665.0	-1822.0	-1752.0
110	-1768.1	-1691.1	-1908.5	-1831.5	-2004.2	-1927.2
120	-1928.9	-1844.9	-2082.0	-1998.0	-2186.4	-2102.4
130	-2089.6	-1998.6	-2255.5	-2164.5	-2368.6	-2277.6
140	-2250.4	-2152.4	-2429.0	-2331.0	-2550.8	-2452.8
150	-2411.1	-2306.1	-2602.5	-2497.5	-2733.0	-2628.0

5.7 40 Gbps DPSK module

The following pictures illustrate the technical characteristics of the 40 Gbps DPSK module. It also gives a view of the schematic block diagram of the 50 GHz and 100GHz setup for OSNR using these modules. The DPSK module that is made by the company L is working in the range between 43.1 Gbps to 44.6 Gbps with a minimum output power of about 3 dBm

- **Company L**:

Technical Specifications

General
- Full C-Band, 100 GHz, and 50 GHz spacing tunable provisioning
- Adaptively tracks and compensates the performance via FEC statistics input.
- Compact, low-power, 300MSA compliant.

Interface Connectors
- Input Interface: LC/PC connectors / SMF-28™ 900 µm Tight Buffer.
- Output Interface: LC/PC connectors / SMF-28™ 900 µm Tight Buffer.

Management
- I^2C Bus MSA compliant

Control
- Different modes of operation:
  - Manual mode of operation with OEM setting optimal operating point.
  - Automatic mode of operation with FEC feedback from OEM host allowing the module to set the optimal operating point.

Physical Dimensions
- 123 x 152.4 x 16 nm. (5 x 6 x 0.61 in.)
- The height can be custom depending on OEM height constraints.
- The height can include an integrated, custom heat sink.

Power
- Power Consumption: 22 W Typical

Environmental Parameters
- Operating temperature 0 to +70 °C
- Storage Temperature: -40 to +85 °C
- Relative humidity: 5 to 80% operating and 5% to 90% short-term

Regulatory Approvals
- Components—all active components will be GR-468-CORE compliant and all passive componetns will be compliant to GR-1221 and GR-1209.
- Laser Safety—comply with 21 CFR 1040.10 and 1040.11 except for deviations pursuant to Laser Notice No. 50 dated June 24, 2007.
- Environmental—GR-63-CORE
- ESD—EN61000-4-2 Electrostatic Discharge Immunity

Optical Specifications

Parameter	Minimum	Maximum	Unit
Transmit Rate	43.1	44.6	Gbps
Frequency Range	191.70	196.10	THz
Output Power	3		dBm
Input Power Range	6	10	dBm
Sensitivity @ input power leading to 1 dB OSNR penalty	4		dBm
Receiver Damage Threshold	14		dBm
DGD Tolerance	8		Ps

Figure 1 OSNR Setup for 50 GHz Specifications

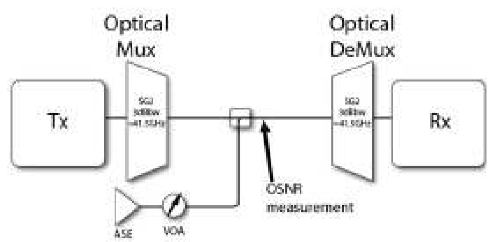
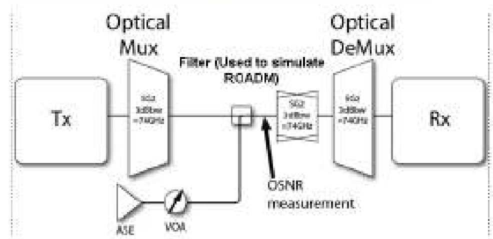


Figure 2 OSNR Setup for 100 GHz Specifications



The transmitter and receiver technical characteristics of the module made by the company M are listed below. As it can be read from the text above the table, this module works over the data rates in the range of 43.02 Gbps to 44.57 Gbps.

- **Company M**:
  - Transmitter

7.1. Data rates

The module supports data rates over the range of 43.02 to 44.57 Gbps with full variability of the data rate over this range. Some optical performance may vary with different data-rates. The data rate is determined by the frequencies of transmit and receive reference clocks supplied by the host card through the 300-pin connector. The module supports a selectable $1/16^{th}$-rate or $1/64^{th}$-rate transmit reference clock and a $1/64^{th}$-rate receive reference clock.

Parameter	Symbol	Conditions	Min	Max	Unit
Average output power	P_{OEOL}	Configurable by I²C command	-1	3	dBm
Maximum average output power	P_{OMAX}	Accuracy is not defined, when transmitter is set to maximum	4	9	dBm
Power stability	ΔP_{OEOL}	Output power stability at fixed wavelength	-0.8	0.8	dBm
		Output power stability across all wavelengths in C-band for output power range of -1 dBm to +3 dBm	-1.6	1.6	
Optical output power in off state	$P_{OUT(tune)}$	Laser disabled		-30	dBm
Laser Relative Intensity Noise (Average)	RIN	Un-modulated laser 1 GHz <= f <= 10 GHz 10 MHz <= f <1 GHz		-145 -110	dB/Hz
Operating frequency accuracy	$f_{OP(t)}$	From the its set frequency listed in Table 1.	– 1.8	+ 1.8	GHz
Modulator chirp	α	P = Po; BER at 10^{-12}, measured with PRBS 2^{31}-1 (refer to ITU-T G.691, Appendix IV)	-0.2	0.2	
Laser line width	Δλ	FWHM		10	MHz
Laser Side Mode Suppression Ratio	SMSR	$P=P_O$	40		dB
Laser mode hopping		Under all operation conditions ($P=P_O$)	None		
Transmitter enable time	$T_{Pswitch\ on}$	From -16 dBm to 90% nominal power		300	ms
		Slow mode	1.3	30	second
Transmitter disable time	$T_{Pswitch\ off}$	From nominal power to -30 dBm	0.2	2	ms
Wavelength switching time	$t_{\Delta switch}$	From I²C command to locked laser signal at f_{OP}		1	second
Transmitter warm-up time	$t_{WARM\text{-}UP}$	From electrical power on to locked laser signal at f_{OP}		60	second
Jitter performance		Conform to ITU-T G.8251, TXREFCK jitter ≤ 1.5ps RMS			ITU Mask
Jitter generation		ITU-T G.8251, demod port of DLI, TXREFCK jitter ≤ 1.5ps RMS — 20 KHz to 320 MHz		0.3	UIpp
		16 MHz to 320 MHz		0.07	
Transmitter return loss	R_{TX}	TX output is connected to a clean connector of the same type	27		dB
Transmitter reflection tolerance	$R_{tolerance}$	Maximum reflection from Tx connector point without impact Tx performance	-14		dB

Table 4: Transmitter optical specifications

o Receiver

Parameter	Symbol	Conditions	43.02 Gbps Min	43.02 Gbps Max	44.57 Gbps Min	44.57 Gbps Max	Unit
Input power	P_R	Required to meet IPDV = 2.5	3	8	3	8	dBm
Optical input power monitor accuracy	P_{mon}	For input power range of 0 dBm to 10 dBm	-1	+1	-1	+1	dB
OSNR required for clock recovery	$OSNR_{Clock}$	Under nominal operating conditions over full operational temperature		9		9	dB/0.1nm
Dynamic OSNR penalty	$\Delta OSNR_{Dyn}$	Input power step change 0.7dB within 50µs (20% to 80% rise/fall times) under normal operating conditions over full operational temperature range at BER = 10^{-3}		0.25		0.25	dB
Dispersion tolerance	CD	Under normal operating conditions over full operational temperature range @ 1.5dB OSNR penalty at BER = 10^{-3}	-40	40	-35	35	ps/nm
Clock recovery chromatic dispersion tolerance	CD_{Clock}	Under normal operating conditions over full operational temperature range with OSNR > 12dB/0.1nm	-230	230	-230	230	ps/nm
Clock recovery DGD tolerance	DGD_{Clock}	Under normal operating conditions over full operational temperature range; OSNR > 15dB/0.1nm		14		14	ps
Jitter tolerance		ITU-T G.8251 OTU3 jitter tolerance mask 8 KHz to 320MHz	Conform to mask		Conform to mask		
Minimum return loss	R_{RX}	RX input port is connected to clean connector of same type	27		27		dB

Table 5: Receiver optical specifications

Conditions		43.02 Gbps			44.57 Gbps			
Optical filter BW	Pre-FEC BER	Typ @ 25°C	WC BOL	WC EOL	Typ @ 25°C	WC BOL	WC EOL	Unit
35 GHz	OSNR @ BER=10^{-8}	19.7	22.1	22.4	21.2	27.5	27.8	dB/0.1nm
	OSNR @ BER=10^{-5}	16.0	18.1	18.4	17.2	19.4	19.7	
	OSNR @ BER=10^{-3}	12.9	13.9	14.2	13.5	14.9	15.2	
	OSNR penalty for 8ps DGD		1.4			TBD		dB
45 GHz	OSNR @ BER=10^{-8}	18.0	23.3	23.6	19.7	27.5	27.8	dB/0.1nm
	OSNR @ BER=10^{-5}	15.2	17.3	17.6	16.2	20.7	21.0	
	OSNR @ BER=10^{-3}	12.5	13.3	13.6	12.9	14.2	14.5	
	OSNR penalty for 8ps DGD		1.3			1.9		dB
75 GHz	OSNR @ BER=10^{-8}	17.7	21.1	21.4	19.9	23.9	24.2	dB/0.1nm
	OSNR @ BER=10^{-5}	15.0	16.8	17.1	15.5	17.9	18.2	
	OSNR @ BER=10^{-3}	12.5	13.3	13.6	12.9	13.8	14.1	
	OSNR penalty for 8ps DGD		1.2			TBD		dB

Table 6: Receiver OSNR and DGD performance specs

5.8 100 Gbps DP-QPSK module

The following pictures outline the technical specification of DO-QPSK 100Gbps modules. It illustrates the data rates that are supported on the client side of this module. 100 Gbps signal is arranged in 50 GHz ITU-T grid.

- **Company N**:

Technical Specifications

The line card offers the following capabilities:

- Multiple Client Options:
  - 10 GbE, OC-192/STM-64, Fiber Channel and OTU2
  - 100 GbE and OTU4
  - 100G 3R Regenerator
  - 40 GbE, OTU3, OC-768/STM-256 and 10G GbE, Fiber Channel, OTU2, OC-192/STM-64
  - Future clients such as SFP+, QSFP, etc
- Supports channelized or concatenated framing
- Full C-Band (and L-band) tunable laser and broadband receiver for flexible wavelength provisioning, minimized sparing costs, and wavelength translation capabilities
- Soft Decision Forward Error Correction for optimized reach up to 2,000 km
- Spectrally efficient for operation at 50GHz channel spacing and through multiple cascaded [R]OADMs
- Operates in DCM-less networks
- Training sequence enables fast dynamic optical network switching
- High CD and PMD Tolerance

Applications

The enables flexible and cost effective transport of data traffic for metro, regional, and long-haul networks. For all applications, using the spectrally efficient PM-QPSK modulation format enables increased reach compared to conventional 10G and 40G systems and operates on standard 50GHz ITU-T grids and over multiple cascaded [R]OADMs.

Operation at 50 GHz channel spacing increases spectral efficiency by at least 2 ½ fold over existing systems, facilitating the highest throughput in a fiber pair available.

It can also be deployed in submarine applications.

Optical Networking Flexibility

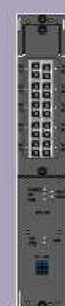
The that has a fully tunable laser and broadband receiver per C-Band (or L-Band) supports client options from 10x10 Gbps, 2x40 Gbps to 1x100 Gbps using the same base board with different plug in options.

Its design with swappable daughter plug-ins lets the operator configure specific line card types that minimizes sparing and warehouse inventory, and future proofs the carrier's investment. Its easy to use management interface, through a Web Uli and SNMP/XML APIs, maximizes service provisioning velocity and reduces complexity.

As traffic demands vary from network section to section and demand growth is difficult to predict, wavelength blocking can become a problem as DWDM networks grow. The supports wavelength translation capability (any 10G and 40G signals maps to a slot in a 100G signal and tunability over the entire C or L band), wavelength blocking is minimized, thus maximizing capacity utilization in carrier networks.

Features and Benefits

- Flexible Client Options for simplified Spare Management
- Provides full G.709 performance monitoring and OA&M capabilities
- Native 100G signal in a 50 GHz ITU-T Grid
- Performs wavelength and client translation
- Full C-Band (and L-band) tunable laser and broadband receiver for flexible wavelength provisioning
- Universal single type of regenerator
- Low cost IPoDWDM router bypass capability
- Training sequence enables fast dynamic optical network switching
- Advanced optical performance monitoring of link Q, CD, DGD and SOP, including real-rime diagnostics



Technical Specifications

General

- Full G.709 performance monitoring and OA&M capabilities
- Full C-Band and L-Band tunable laser and broadband receiver for flexible wavelength provisioning
- Hardware Client Support for
  - 10G: XFP: OC-192/STM-64, 10GbE, OTU2 and FC
  - 40G: CFP: OC-768/STM-256, OTU3
  - 100G: CFP 100 GbE, OTU4
- Compact, low-power, rack mount unit (Shelf contains slots for any mix of eight cards)

Interface Connectors

- Line Interface: LC/PC Connectors

System Management

- RS-232 craft interface
- Auto-sense switched 10/100 Mbps Ethernet LAN interface
- Local/Remote (Telnet) CLI for initial configuration (GR-831-CORE)
- Embedded HTTP Server with Web GUI for full provisioning and management support
- SNMP and XML Full provisioning and management support
- Full performance monitoring capability: Client G.709 Section and Path Overhead, Optical Power

Physical Dimensions

(HxWxD): 353.32 x 60.45 x 300 mm
13.91 x 2.38 x 11.81 in.
Shelf (HxWxD): 666.75 x 538.48 x 300 mm
26.25 x 21.20 x 11.81 in.

Power

- External: -40 to -75 VDC, -48 VDC Nominal
- Input Power: 240 W Maximum

Environmental Parameters

- Operating Temperature -5 to +40 °C (Shelf Inlet)
  (Up to 55 °C for a period less than 96 consecutive hours)
- Maximum Altitude: 5905 ft / 1800 m
- Relative humidity: 5 to 90% Non-Condensing

Regulatory Approvals

- Safety: UL 1950
- EMI/EMC: FCC part 15, Class A
  GR-1089-CORE
  CISPR22
- Telecom: GR-253-CORE
  GR-2918-CORE
- NEBS (Level 3) GR-63-CORE
  GR-1089-CORE

Line Interface Specifications

Transmit

Parameter	Min	Max	Units
Frequency Range	191.35	196.1	THz
Output Power	-1	2	dBm
Output Power tuning granularity		0.2	dB
Output power reading accuracy		0.5	+ or- dB
Output power Stability		1	+ or- dB
Operating Frequency	F_{ITU}-2.5	F_{ITU}+2.5	GHz
Optical Reflectivity		-27	dB
Side Mode Suppression Ratio	40		dB
Optical Output power during Frequency Tuning		-35	dBm

Receive

Parameter	Min	Max	Units
Frequency Range	191.7	196.1	THz
Input Power Range	-18	0	dBm
Overload Power	5		dBm
Optical Signal to noise ratio		14	dB
Chromatic Dispersion Penalty		0.5	dB
Chromatic Dispersion Tolerance		±40000	ps/nm
DGD Tolerance	100		ps
Chromatic dispersion + PMD Penalty		0.5	dB
Optical Bandwidth Tolerance	28	80	GHz
Dynamic PMD Penalty		0.5	dB
Polarization Dependent Loss Penalty		0.5	dB