Milestone MJ1.2.3: White Paper – Optical Reach of Photonic Services

Milestone MJ1.2.3

Grant Agreement No.:	238875
Activity:	JRA1
Last Updated:	05-09-2013
Task Item:	Task 2
Target Audience:	NREN technical networking specialists
Dissemination Level:	PU (Public)
Document Code:	GN3-13-162
Authors:	P. Škoda (CESNET), J. Vojtech (CESNET)

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7 2007–2013) under Grant Agreement No. 238875 (GÉANT).

Table of Contents

Table of Figures

Table of Tables

1 Introduction

Fibre optic communications were enabled by two major developments: semiconductor laser capable of operation at room temperature and improvement of optical fibre attenuation down to 0.2 dB/km in 1550 nm region. Note: today state-of-the-art pure silica core fibres have attenuation of about 0.15 dB/km. Despite this low attenuation, the reach is limited due to minimal sensitivity of the receiver. In the original generation of transmission systems, the reach was extended by periodical signal regeneration, where the signal was received, amplified in the electrical domain and was transmitted with new timing. This configuration is quite unpractical as a regenerator can regenerate only a single signal and it is not fully speed- and protocol-agnostic. Major capacity improvements were achieved by the introduction of wavelength division multiplexing and optical amplification, where each amplifier amplifies all signals simultaneously. On the other hand, amplification introduces noise and the presence of many signals in the fibre can introduce some non-linear effects.

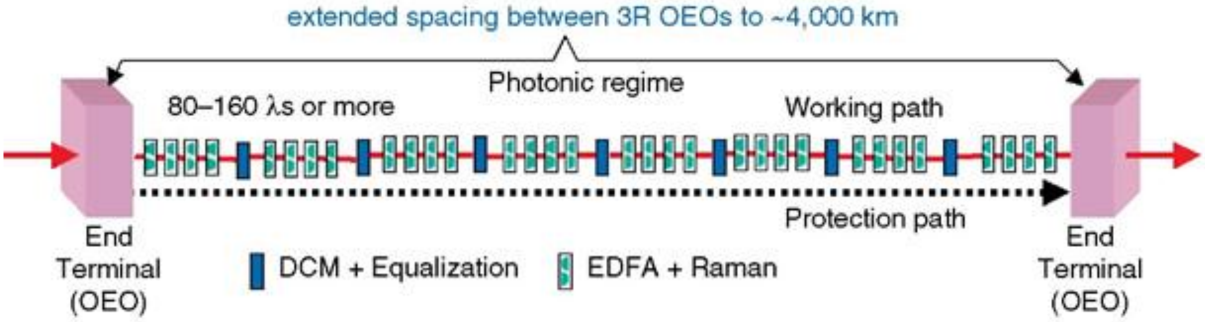

Figure 1.1: Principle of amplified point-to-point transmission system

2 OSNR Limited Reach

The unregenerated optical reach is influenced by many factors such as attenuation, dispersion, Optical Signal to Noise Ratio (OSNR) and nonlinear effects. While the first two can be easily overcome by optical amplification and dispersion compensation, OSNR and nonlinear effects pose true limits to unregenerated optical reach. Nonlinear effects can be minimised by the use of shorter spans with lower signal peak powers or the use of fibre types with low non-linear coefficient, but OSNR is degraded at every amplification site by added Amplified Spontaneous Emission (ASE) noise. OSNR is simply defined as:

$$OSNR = \frac{signal\ power}{noise\ power}$$

Considering ASE noise only, we can write for a single amplifier the following equation:

$$OSNR_{one} = \frac{P_{out}}{P_{ase}} = \frac{P_{in}\ .\ G}{P_{ase}} \quad (1)$$

where P_{out} is amplifier output power, P_{in} is amplifier input power and G is amplifier gain. Based on **[1]** we can describe P_{ase}:

$$P_{ase} = 2.n_{sp}.(G-1).h.v.\partial f \quad (2)$$

where n_{sp} is the population inversion factor of the optical amplifier, h is Planck constant, v is optical frequency and ∂f is the optical bandwidth of the receiver. We substitute (2) into (1) and receive (3), where the noise Factor (F) of the amplifier is expressed in (4).

$$OSNR_{one} = \frac{G.P_{in}}{2.n_{sp}.(G-1).h.v.\partial f} = \frac{P_{in}}{F.h.v.\partial f} \quad (3)$$

$$F = \frac{2.n_{sp}.(G-1)}{G} \quad (4)$$

Noise Factor can be further expressed in decibels as a Noise Figure (NF):

$$NF = 10log_{10}(F)$$

Assume we have N cascaded amplifiers with Noise Factors F_i and gains G_i, where gains exactly cover the attenuation between particular amplifiers. Also assume that all F_i are the same and equal to F and also G_i are the same and equal to G, i.e. amplifiers are spaced equidistantly. We can express the total noise Factor F_{tot} as in (5):

$$F_{tot} = F_1 + \sum_{i=2}^{N} \frac{F_i - 1}{\prod_{j=i}^{N} G_{j-1}} = F.(G-1).N \quad (5)$$

The total OSNR can be expressed by substituting F_{tot} (5) into (3) as F:

$$OSNR_{tot} = \frac{P_{in}}{F.(G-1).N \cdot h.v.\partial f} \quad (6)$$

$OSNR_{tot}$ in decibels:

$$OSNR_{tot\,dB} = P_{in} - G_{dB} - NF - 10log_{10}(N) - 10log_{10}(h.v.\partial f)$$

where P_{in} is expressed in dBm, amplifier gain *G* and *NF* are expressed in decibels. The last term is equal -58 for ∂f of 12.5 GHz, *v* of 193 THz and *h* of 6.626x10^{-34}. So we can write final equation:

$$OSNR_{tot} = 58 + P_{in} - G_{dB} - NF - 10log_{10}(N)$$

Every optical receiver requires a signal of some OSNR, in order to successfully receive the information with the given Bit Error Ratio (BER).

We can divide photonic services (PSs) into two principal groups. The first group represents relatively slow PSs maintaining exact signal timing but not offering huge transmission capacities. For such PSs, electronic processing is unsuitable, so they do not perform Forward Error Correction (FEC) and require relatively high OSNR **[2]**.

Table 2.1 summarises the required OSNRs for 1G, 2.5G and 10G services and unregenerated optical reach for two different scenarios based on the theory above.

- Scenario 1: Span 80 km, Gain 18 dB, NF 6 dB, Pin 0 dBm.
- Scenario 2: Span 100 km, Gain 22 dB, NF 6.5 dB, Pin 0 dBm.

Bit rate	Type of modulation	Minimal OSNR accepted	Optical Reach 1	Optical Reach 2
1 Gbit/s	NRZ	7 dB	40 000 km	17 000 km
2.5 Gbit/s	NRZ	11 dB	15 920 km	7000 km
10 Gbit/s	NRZ	17 dB	4 000 km	1700 km

Table 2.1: Required OSNR and unregenerated reach for first type of photonic services

Note: In this case we do not take into account the influence of nonlinearities, and in the case of 2.5G and 10G transmission it is considered that CD is compensated, by the use of balanced fibre with a positive and chromatic dispersion coefficient.

The second group of photonic services offers relatively huge transmission capacities and electronic processing as enhanced FEC **[3]**, **[4]**. Table 2.2 below summarises the required OSNRs for fast data services and unregenerated reach for two different scenarios.

Bit rate	Type of modulation	Minimal OSNR accepted	Optical Reach 1	Optical Reach 2
10 Gbit/s	NRZ	8.5 dB	28 320 km	12 500 km
40 Gbit/s	DPSK	11.5 dB	14 160 km	6 300 km
40 Gbit/s	PM-QPSK	10.2 dB	19 120 km	8 500 km
100 Gbit/s	PM-QPSK	14.2 dB	7 600 km	3 300 km
400 Gbit/s	PM-16QAM	22.4 dB	1 120 km	500 km

Table 2.2: Required OSNR and unregenerated reach for second type of photonic services

The last three modulations are supposed to use coherent detection and digital signal processing, so they are operated without any CD compensators. In such a case, based on work **[5]**, we can make the following assumptions: nonlinear noise is additive. When launch power is optimal, the power of nonlinear noise is half of ASE power. Adding this noise power to formula (1), it increases *F* of the amplifier by 1.5 times. Table 2.3 summarises unregenerated reach for coherent PSs with the influence of nonlinear additive noise.

Bit rate	Type of modulation	Minimal OSNR accepted	Optical Reach 1	Optical Reach 2
40 Gbit/s	PM-QPSK	10.2 dB	13 040 km	5 600 km
100 Gbit/s	PM-QPSK	14.2 dB	5 200 km	2 200 km
400 Gbit/s	PM-16QAM	22.4 dB	720 km	300 km

Table 2.3: Unregenerated reach for coherent photonic services with influence of nonlinearities

Note: In the case of the second group of photonic services, we do not take into account reach limits or penalties caused by CD, PMD or optical filtering.

3 Conclusion

The estimated unregenerated optical reaches are based on OSNR budget modelling for a homogenous telecommunication network with equidistantly spaced amplifiers with the same gain and noise figures. Attenuation of each span is fully covered by amplifier gain. The model assumes the network to be dispersion compensated and ideally amplified. Moreover, nonlinear effects are considered only for coherent transmissions.

It can be seen that the first type of photonic services with lower bit rates can offer good unregenerated optical reach, despite missing FEC processing. For example, time transfer using time stamps at a rate of several Hz can have required OSNR close to 3 dB and therefore very high unregenerated optical reach. The second type of PSs can also offer reasonable unregenerated reaches, which can be further increased by amplifier NF decrease, fibre attenuation decrease or increase of FEC coding gain. For example, with amplifiers of NF=5, a fibre attenuation coefficient of 0.18 dB/km and 1dB FEC gain, an improvement in unregenerated reach of about 18 400 km can be achieved for 100G DP-QPSK in scenario 1.

References

[1] Zyskind John, Srivastava Atul,"Optically Amplified WDM Networks", Academic Press 2011

[2] ITU-T: Optical Transport Network (OTN) Tutorial http://www.itu.int/ITU-T/studygroups/com15/otn/OTNtutorial.pdf

[3] Downie John D., "112 Gb/s PM-QPSK transmission systems with reach lengths enabled by optical fibers with ultra-low loss and very large effective area"

[4] Robust Optical Transmission Systems Modulation and Equalization http://www.fujitsu.com/downloads/TEL/fnc/whitepapers/Beyond-100G.pdf

[5] Pierluigi Poggiolini, "Modeling of Non/Linear Propagation in Uncompensated Coherent Systems"

Glossary

ASE	Amplified Spontaneous Emission
BER	Bit Error Ratio
CD	Chromatic Dispersion
F	Noise Factor
FEC	Forward Error Correction
G	Gain
NF	Noise Figure
NRZ	Non-Return to Zero
OSNR	Optical Signal to Noise Ratio
P	Power
PMD	Polarisation Mode Dispersion
PS	Photonic Service