Abstract: The design and operation of optical transparent networks requires some physical layer awareness that is obtained through physical modelling. We show in this paper that the operator context adds some constraints for the design and use of these models.

Keywords: Physical impairment modelling, optical networking, transparency, impairment awareness.

Introduction

Impairment awareness has been introduced in routing algorithms in the late 1990’s in order to cope with transparency concepts [1]. Indeed, the introduction of transparency in optical core and metro networks, mainly driven by cost (CAPEX and OPEX) reduction introduces some sort of revolution in the optical layer: paths that were previously feasible by design (concatenation of regenerated sections), may no more be feasible because of accumulated impairments. Performing network planning and dimensioning in such context thus requires taking into account paths “physical feasibility”. In order to integrate this feasibility assessment in the network planning phase, it has been proposed to model physical performances (represented by the Q-factor, Quality factor, or BER, Bit Error Rate) using simple relations between impairments suffered by paths and their physical impact [2]. Since then many models have been proposed in the literature [3-7] and the concept of physical layer awareness has been extended to the network operation, for example to set-up a lightpath in a transparent network [8]. All proposed models rely however on a very simple hypothesis: that all required parameters needed to compute estimated performances are available. In this paper we verify the validity of such hypothesis in the context of an operator network and discuss the alternatives to performances estimation. The rest of the paper is organized as follows: section 2 summarizes main parameters used in models and assesses their accuracy. Section 3 presents models accuracy related to infrastructure diversity. Section 4 concludes the paper and proposes some solution to overcome the models limitations.

2. Physical parameters in real networks

2.1 Models

Purpose of physical modelling in the context of planning or routing is not to optimize transmission system performances or to study physical effects impact. Physical modelling in this context is to evaluate lightpath feasibility with respect to a given transmission system in a simple and fast enough way to be integrated in routing algorithms. Models proposed in the literature are thus approximations. They usually relate the performances in terms of BER or Q factor, using Personick Q factor expression and its relation with BER [9] on the one hand and OSNR on the other hand, thanks to simplified relation between Q and OSNR [10]. Impairments are integrated in the models as “noise variance” in the Q expression [2] or as OSNR penalties [3]. Some models also use separate expressions and thresholds for impairments using empirical or semi-empirical rules [6][7]. The approximations used to derive models result in inaccuracies both due to network representation accuracy and to modelling.

2.2 Network representation

As explained before, modelling in the context of planning and dimensioning requires the computation of impairments contribution. Main impairments included in models are: noise accumulated by amplifiers, crosstalk due to channel overlapping, inter symbol interference due to chromatic dispersion or polarisation mode dispersion, pulse distortion due to non-linear effects such as self phase modulation, cross-phase modulation or four wave mixing. Reader can refer to references for more details on the models integrating these effects. Several parameters are required from the network to compute impairments contribution. For example:

- Noise contribution requires the number of amplifiers and their gain and noise figures values as well as the channel power.
- Chromatic dispersion (CD) contribution requires the contribution from each fiber span and each dispersion compensating modules (DCMs) inside the lightpath under study.
- Polarisation mode dispersion (PMD) requires the contribution of each fiber span, amplifier, dispersion compensating modules and any other equipment inside the lightpath under study
- Self phase modulation (SPM) requires the length as well as the attenuation, the non linear index and the effective area of each fiber spans. It also requires the channel power as well as the signal modulation format and bitrate.

From these examples, we see that impairments contribution are computed based

- on fibers characteristics (such as length, attenuation, chromatic dispersion, polarisation mode dispersion, non linear index, effective area, …),
- on transmission equipments characteristics (such as gain and noise figure of amplifiers, chromatic dispersion of dispersion compensating modules, node crosstalk, devices polarisation mode dispersion and polarisation dependant loss, …),
- and on transmission system design characteristics (channels and amplifiers numbers, channel power,
2.3 Parameters accuracy

First, because equipments and fibres have been installed at different periods and well before transparency introduction, only some of these parameters have been collected and recorded in databases. For example effective areas of fibers are usually not recorded. When PMD was not an identified problem for transmission (for 2.5 Gbit/s systems or below for instance), PMD contribution of fiber spans may also have been neglected. Secondly, although operators maintain accurate view on their own fibers infrastructure, before transparency concept introduction there was no need to make databases heavier with data not used for the network management. Indeed, in opaque network the only relevant information for network planning was that links were set up and working with enough system margins to ensure repairs and maintenance operations, and not the detail of amplifier characteristics, DCMs, .... As a result, databases and operational processes may not be always well adapted to include such details.

Besides historical and operational reasons that lead to databases inaccuracy because of missing parameters, inaccuracy has also other sources:

- precision of measurement equipments or processes: for example PMD measurement accuracy is between 10% and 20% in France Telecom network [11];
- ripples around nominal value at measured wavelength (for example, gain and noise ripples [12]);
- fluctuation in time due to environment change or ageing (for example temperature seasonal change leads to CD variation [13] that may be relevant for 40Gbit/s bit rate and higher).

If missing parameters are indispensable to performances estimation but can not be measured, a solution consists in using standards specifications or network samples. We consider for example the case of the France Telecom network where fibers have been installed at various periods (from 1980's) with different vendors. This results in a large dispersion of values for parameters although all fibers are compliant with ITU-T G.652 standard. This is illustrated in figure 1 for the CD parameter of more than 1500 fibers of France Telecom infrastructure. Supposing that effective area of fibers is required by the model, as it has not been measured in the field it is necessary to give an estimate with error range. Because of the diversity of the infrastructure shown for CD in Figure 1, we can also expect that same diversity applies for fiber effective area. Indeed, laboratory measurements on various samples of fibers show that expected dispersion around nominal value for mode diameter (used to compute effective area A_eff) is around 9.1±0.5 µm at 1310 nm, leading to a variation of A_eff of almost 80±20 µm at 1550 nm.

Applying models with current uncertainties may lead to erroneous results: errors in the number of regenerators in dimensioning and planning studies, erroneous feasibility estimation for lightpath set-up. So planning models should include parameters uncertainty and inaccuracy in their design for example through additional margin, level of confidence or error range. This requires a "precise" identification of the uncertainties and eventually the definition of some process for the operators to include all relevant parameters in their databases.

Although, we can expect that future "transparent" or "translucent" transmission system equipments include many of the required parameters in management information databases and that fiber databases will also be updated, some parameters will probably never be measured (such as effective areas of fibers) and the others will still be subject to inaccuracy due to the precision of measurement equipments for example.

3. Designing models for real networks

Previous section has highlighted the uncertainties that impair the validity of models results. This is not the only degrading factor for models accuracy. An important factor is also related to the amount of approximations that has been made to derive the physical model. We recall that the purpose of models in the context of this paper is to guarantee that all impaired lightpaths are correctly identified and rejected while the number of rejected "correct" lightpaths is minimized. In this section we show that it is important to consider real network conditions to design these models.

For this purpose, we derive two simple semi-empirical models based on two network conditions: homogeneous infrastructure and real infrastructure. The design of these models is based on the performances of all shortest paths in the network. A third model is used to emulate performance measurement. The network under study is a pan-European network whose characteristics are given in table 1. The two simple models are:

- Model 1 uses a simple threshold for OSNR. Below OSNR_{min}, it is considered that lightpaths are not feasible.
  \[ \text{OSNR} \geq \text{OSNR}_{\text{min}} \] [1]
- Model 2 uses a threshold for OSNR and a limit on PMD. If OSNR is below OSNR_{min} and if PMD is over PMD_{max}, it is considered that lightpaths are not feasible.
OSNR $\geq$ OSNR$_{\text{min}}$ and PMD $\leq$ PMD$_{\text{max}}$ [2]

Table 1: Studied network topology

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<thead>
<tr>
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<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
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<td>Network size</td>
<td>92 nodes</td>
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</tr>
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OSNR$_{\text{min}}$ for model 1 and 2 and PMD$_{\text{max}}$ for model 2 must be computed in such a way that any impaired lightpaths shall be correctly rejected. We use results from the third "reference" model that emulates experiments and derive OSNR$_{\text{min}}$ and PMD$_{\text{max}}$ for all shortest paths in the network.

For the purpose of this paper, the third model (model 0) is considered to be precise enough to emulate "real" performances measurement (if it were done). It calculates penalties on OSNR to account for several impairments. Separate limits on penalties and impairments determine the domain of validity of model 0.

OSNR $\geq$ OSNR$_{\text{min}0}$ and $\text{Pen}_{\text{PMD}} + \text{Pen}_{\text{CD}} < \text{Pen}_{\text{max}}$ and $\phi_{\text{NL}} < \phi_{\text{NLmax}}$ [3]

Where:
- $\text{OSNR}_{\text{min}0} = \text{OSNR}_{\text{thres}} + \text{Pen}_{\text{PMD}} + \text{Pen}_{\text{CD}}$
- $\text{Pen}_{\text{PMD}} = a \text{PMD}^2$
- $\text{Pen}_{\text{CD}} = b \text{CD}_e^2$
- $\text{CD}_e = (\text{CD} - \text{CD}_c) / (1 - \phi_{\text{NL}})$
- $\text{CD}_c = d \phi_{\text{NL}}^2 + e \phi_{\text{NL}}$

OSNR$_{\text{thres}}$ represents the minimum required OSNR at receiver side for error free performance, in the absence of PMD, CD and non linear effects. Pen$_{\text{CD}}$ and Pen$_{\text{PMD}}$ represent the penalties on OSNR accounting for CD, non linear effects and PMD degradation. CD$_e$ is included to account for non linear effects impact on the CD tolerance of the receiver. OSNR$_{\text{min}0}$ represents the minimum OSNR required at receiver side including all impairments. Values for the different constants $a$, $b$, $c$, $d$, and $e$ shown in table 2 were derived for a 10Gbit/s NRZ WDM system with 100GHz channel spacing [14].

Table 2: Numerical application

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In figure 2 we have drawn some of the computed impairments (OSNR in dB, PMD in ps, non linear phase shift, PhiNL, as defined in [15], in rad) for all possible shortest paths in the network under study. In this figure we have considered the homogeneous case where all fibers have identical characteristics (same per km CD, PMD, attenuation, same effective area).

In the figure 3 we have drawn the same impairment contributions accounting for real values for CD, PMD and attenuation. Design rules and amplifier types are identical in both cases. Red points in figures 2 and 3 represent the computed OSNR$_{\text{min}0}$ of model 0 which is the minimum required OSNR to ensure sufficient performances for each plotted lightpath.

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If the model 1 is designed using homogeneous network conditions, setting OSNR$_{\text{max}}$ to 18 dB guarantees that all impaired lightpaths are correctly rejected while the number of rejected correct lightpaths is minimized (13% of all the correct shortest lightpaths with respect to model 0). Model 1 however does not work for the heterogeneous network, because some impaired lightpaths (about 3%) in this case are not correctly rejected. This result can be explained in the following way: because of the homogeneous condition, the impairments are relatively well correlated. As a result, penalties due to impairments increase almost in the same
proportion for all lightpaths when OSNR decreases. In the heterogeneous real network, reversely, impairments are de-correlated and high penalties due to impairments other than noise can arise even for high values of OSNR. The OSNRmin of model 1 should be increased to 20 dB to guarantee rejection of all impaired lightpath in the heterogeneous networks. This increase results in about 42% rejection of correct lightpaths. With this simple example we want to show that increasing model complexity can improve model accuracy.

Similarly, if model 2 is designed with homogeneous network optimum values for OSNRmin and PMDmax would be 17dB and 9ps respectively resulting in 5% of correct paths rejected. But again the model would not be error free for the real heterogeneous network. For this network, values should be set to 18 dB and 19 ps for OSNRmin and PMDmax respectively, leading to 13% of correct paths rejection. With this second example we want to show that increasing model complexity can improve model accuracy.

The number of rejected correct paths has a direct impact on the dimensioning and on the cost of the network. For example using model 1 with the real network (with OSNRmin = 20 dB) would result in 2217 more regenerators than with model 2 if all shortest paths were to be set-up. This example clearly shows the importance of integrating the fibre and equipment diversities during the design of the physical models.

4. Conclusion

In this paper we have underlined the importance of considering real infrastructure conditions for the design and the use of physical models in the context of planning, dimensioning, or operation of optical transparent or translucent networks. Indeed both parameters inaccuracy and fiber diversity have impacts on these models. On the one hand, parameters inaccuracy widens the error range of models and requires some additional margin to guarantee correct lightpaths feasibility estimation. As a result, inaccuracies reduce the interest for very precise and complex models using many parameters, as the precision will be masked by margins. On the other hand, fiber diversity clearly shows that simple models relying on a small number of parameters result in an increase of rejected correct paths, thereby reducing the interest for transparency because of the associated reduction of effective transmission maximum reach. Finding the correct trade-off between the models accuracy and the parameters accuracy is thus a key issue.

We believe that the solution to this trade off is a good compromise between parameters measurement and complexity of models. For example new equipments able to measure CD, PMD, OSNR in a non intrusive way [16] could help to update fibers database without cutting in service traffic. However the additional cost of such measurement facilities should be smaller than the amount of savings provided by transparency, for this concept to be attractive.

Finally real testing of lightpaths in the case of lightpaths set up, is an interesting alternative to modelling as performances are directly measured and not computed, avoiding the problem of precision. The method however slows the lightpath set-up process and only gives instantaneous performance estimation (that may greatly vary with PMD effect for example). The combination of probe testing and modelling as proposed in [17] could be a way to increase reliability of feasibility estimation, especially in the case of incomplete physical databases or inaccurate models. This solution however cannot be applied to dimensioning and planning studies as it requires direct measurements of established lightpaths.

5. References


