Current aspects of optical performance monitoring and failure root cause analysis in optical WDM networks

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ABSTRACT

Currently existing dense wavelength division multiplexing (DWDM) networks start to migrate from numerous point-to-point links towards meshed, transparent, optical networks with dynamically routed light paths. This increases the need for appropriate network monitoring and supervision methods. Optical performance monitoring (OPM) has to be cost-effective. Thus additional spendings for OPM have to be significantly smaller than the savings in OPEX due to increased reliability and ease of operation, administration, and maintenance (OAM). We elaborate on different advanced monitoring concepts. First, we discuss general failure scenarios in meshed networks. Then we describe software based failure root cause analysis and its implementation. We conclude that by implementing appropriate software algorithms in the network hardware effort can be significantly reduced. Finally, we assess different advanced OPM methods which may show up as useful to enable OPM in future optical networks.

Keywords: WDM, optical networking, optical performance monitoring, failure root cause analysis, signal distortions, adaptive equalization, BER, Q-factor, polarization nulling, equalizers

1. INTRODUCTION

Data transmission using DWDM represents the backbone of today's high capacity telecommunication networks. Steadily growing channel counts, data rates, and system reach increase the sensitivity of optical networks to nonlinear effects. Furthermore, the increasing complexity of dynamically routed meshed optical networks makes the data transmission network vulnerable to network malfunctions, misconfigurations, and traffic affecting signal impairments. Thus OPM is of high relevance to supervise the network's performance and to maintain high signal quality [1-4].

OPM and failure root cause analysis facilitate fast fault detection, error root cause identification, and therefore enable operators to do fast error cancellation [5,6]. OPM further facilitates network optimization, system setup and upgrade as well as network maintenance[7]. In summary OPM and failure root cause analysis are essential tools to reduce OPEX in complex dynamic DWDM networks. As cost-effectiveness is a key issue for novel technologies to be added to commercial transmission systems one has to work out exact needs of individual networks to minimize OPM effort and to maximize its benefit.

We start with a discussion of OPM aspects in meshed dynamic optical networks. In contrast to standard point-to-point links in a meshed network the site where an error occurs and the location where its root cause has entered the network needn't to be in a common place. Consequently, OPM and failure root cause analysis have to fulfill enhanced requirements in order to detect signal degradations and to identify corresponding reasons. Next we review advanced OPM technologies and discuss different aspects of their utilization. We highlight advantages and disadvantages of individual OPM concepts and measurement techniques. We assess their potential application with respect to the technical and functional requirements of dynamic meshed optical networks. Major attention is drawn to the cost-effectiveness of considered technologies. Further, we evaluate related technical effort for implementation as well as operational benefits. The usability of derived measurement parameters for the purpose of failure root cause analysis will be discussed.

2. MESHED, DYNAMIC WDM NETWORK

In this paper we consider a general meshed optical network, which can be reconfigured dynamically (cf. Fig. 1). Switching events or channel/power reconfigurations inside the network change the physical constraints of affected multiplex sections. This in turn can change channel interaction and thus may lead to cross-talk and network failures.

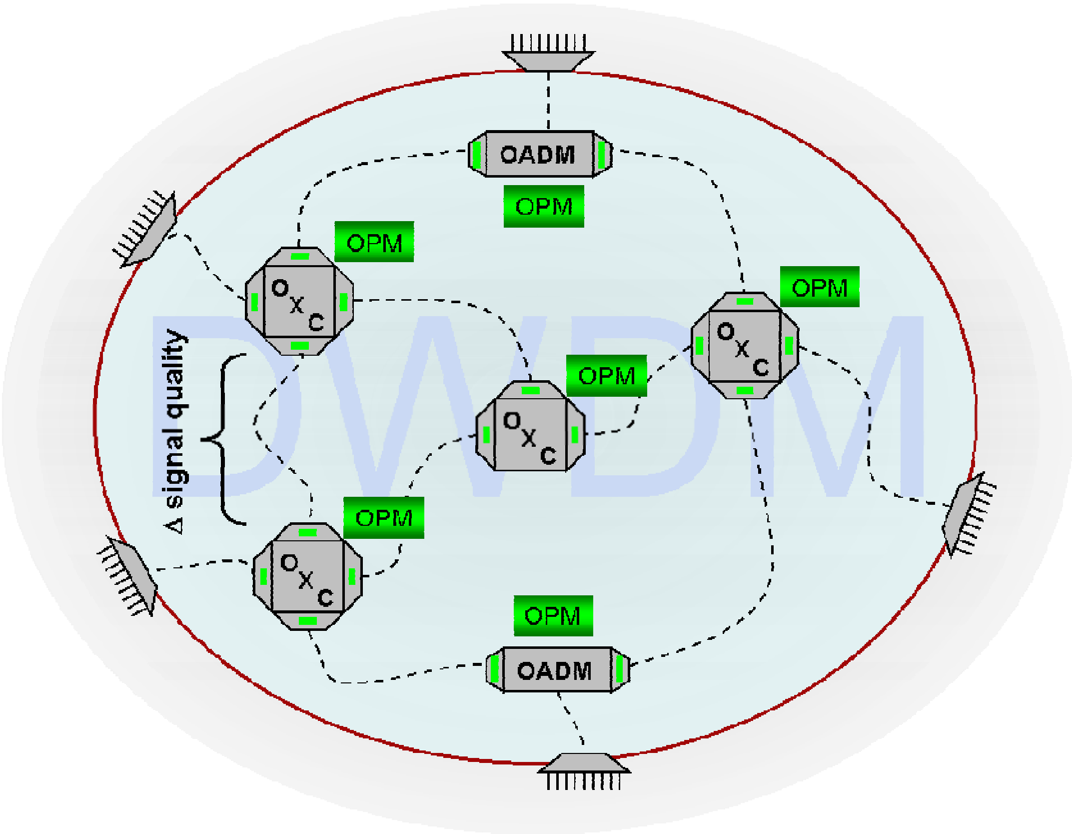

Fig. 1: Example of a dynamically routed meshed optical network comprising OPM functionalities in every network node.

Regarding dynamic meshed networks, two major problems occur with respect to OPM and failure root cause analysis.

1) Dynamic switching of wavelengths requires that OPM measurements are much faster than switching intervals. Data have to be continuously updated to facilitate failure root cause analysis.

2) The meshed nature of the network results in the possibility that error alarms and their root causes might not be within the same site, multiplex section or even the same channel. Thus, the current status of the network and its topology has to be known to enable failure root cause analysis, error localization and cancellation.

If these topics are addressed well, OPM and failure root cause analysis can significantly ease OAM and reduce OPEX.

There are many failures which can happen on an optical link. But this number even increases when going from point-to-point links to meshed networks. As a network is more than just the sum of its links new kinds of failures join those already known from point-to-point links. In the following we will discuss three major examples.

2.1. Error root cause within the channel

In this case the respective channel suffers a severe degradation due to an error in a node, e.g. erroneous switching or attenuation, or errors on a link along the path, e.g. attenuation or amplification (cf. Fig.2). However the failure root cause can be identified rather easily as the channel performance directly correlates with alarms or the channel settings along its path.

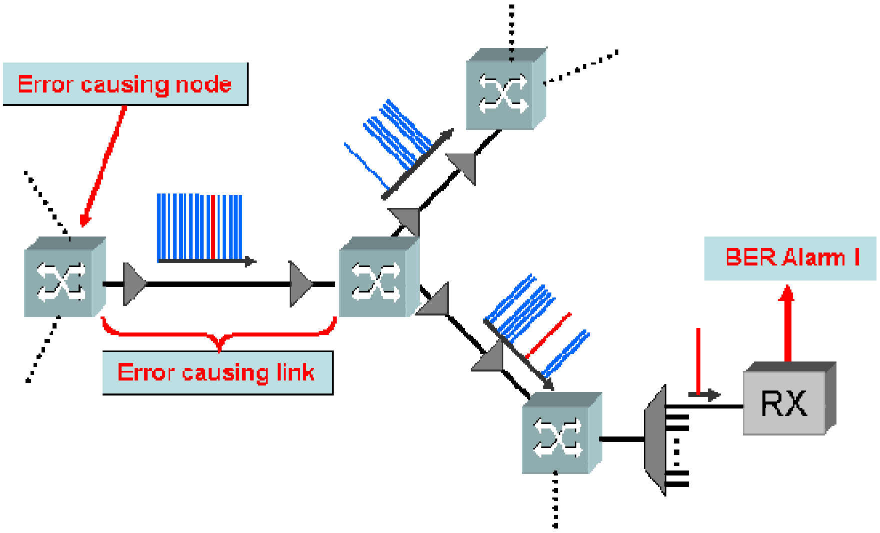

Fig. 2: Example of an error which root cause is within the same channel.

2.2. Error root cause along the path / transferred via x-talk from other channels

In the second case the strong signal degradation is introduced via cross-talk from other co-propagating channels. Reasons for this are for instance a wrong Raman tilt compensation or too high power levels introducing nonlinear crosstalk. Such a behavior is depict in Fig. 3. However the error root cause is still located along the channel path.

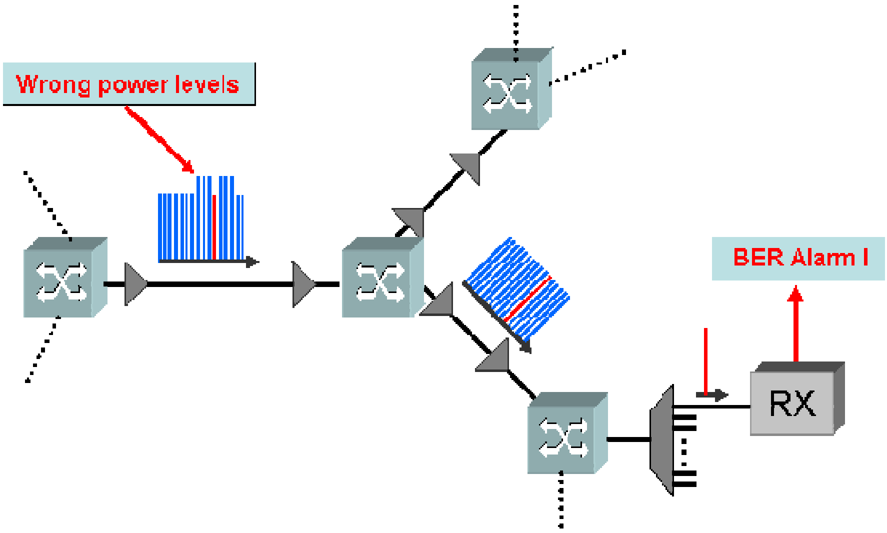

Fig. 3: Introduction of nonlinear cross talk due to wrong power settings in adjacent co-propagating channels.

2.3. Error root cause not along the path / transferred via x-talk from other channels

The third and worst error scenario is a failure happening anywhere in the network, which causes severe signal degradations to the considered channel. For instance an erroneous node drops all existing channels. These channels then miss in the following links. This may change channel interaction elsewhere in the network. The degradation of the considered channel is not directly affected by the erroneous node. However, it is introduced by other co-propagating channels, e.g. channels now missing due to a malfunction in the erroneous node. Fig. 4 depicts this effect on the example of the Raman effect.

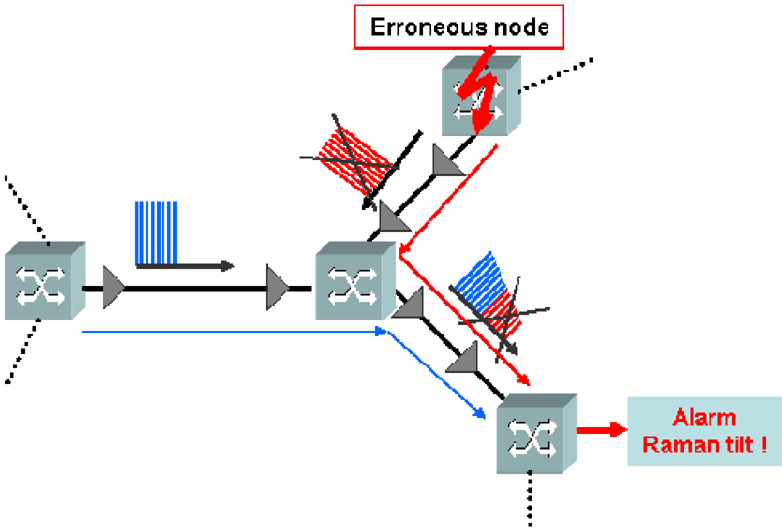

Fig. 4: Error due to wrong Raman compensation after a drop of many channels at a different site.

These three examples above describe the problem of OPM and failure root cause analysis in optical networks. The key issue is not just to detect a signal degradation but to determine its root cause in the network in order to react correspondingly and to enable fast and purposeful error cancellation.

3. ALARM AND EVENT CORRELATION

According to the considerations above it is obvious that in future, dynamic, meshed networks failure root cause analysis cannot only base upon measurements in the optical domain. This would be by far too complicated and expensive. Instead it is useful to consider possibilities of alarm and event correlation in order to identify and localize root causes of severe alarms and channel degradations. Useful available information facilitating this is the knowledge about

- Channel path and channel history
- Network topology, configuration and status
- Recent events
- Current network element alarms

The knowledge about recent events and changes may provide first indicators of what might be the reason for currently alarmed network malfunctions. Then the topology pinpoints dependencies between current alarms and recent events in the network. By filtering all this information and correlations, temporal as well as spatial, and evaluating this based on algorithms taking physical effects into account one can bring down the number of possible failure and alarm root causes to just a few or even one. Additional OPM data measured at certain points in the network have to be used to identify finally the basic root cause of the errors or alarms. Fig. 5 depicts this concept of correlation.

Considering this approach the necessary OPM hardware and its accuracy is defined by the missing information necessary to unambiguously identify relevant root causes. In return, by utilizing advanced alarm correlation it is no longer necessary that OPM measurements provide complete information about signal degradations and root causes. Consequently, OPM hardware and related costs can be reduced down to a minimum.

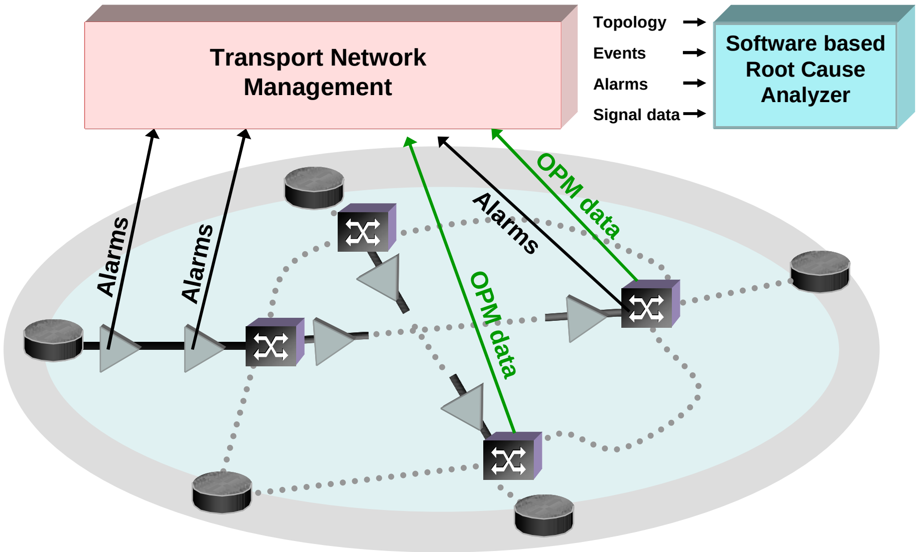

Fig. 5: Concept for alarm and failure root cause analysis in meshed networks based on alarm and event correlation.

4. OPM REQUIREMENTS IN FUTURE DYNAMIC MESHED OPTICAL NETWORKS

The sections above have described additional requirements in meshed dynamic networks. Hardware effort for OPM can be reduced by implementing advanced data correlation algorithms. Next, we will discuss key requirements of OPM modules in general. This is essential to elaborate an appropriate hardware concept which will meet market requirements. Key requirements regarding OPM components and subsystems are:

- **Small size:** As floor space is costly size directly translates into OPEX and should be as small as possible.
- **Fast measurements:** In dynamically routed networks OPM measurements must take place much faster than reconfiguration intervals. Additionally in case of a sudden system crash a system restart based on current OPM data should be possible immediately.
- **Operation at low input power:** Usually OPM hardware is connected to the system via tap-coupler providing just a small amount of signal power.
- **Multi-channel operation:** To reduce hardware effort advanced OPM modules should be capable of monitoring several channels in parallel or consecutively.
- **Bit rate and modulation format transparence:** As mixed traffic can be present on the line or signal formats may change during lifetime the OPM technique should be capable of monitoring various data rates and modulation formats.
- **Flexible measurements:** The OPM module should be utilizable anywhere in the network regardless local properties e.g. local accumulated dispersion.

Additional requirements regarding OPM hardware are that it should be

- Passive / not service affecting
- Remotely configurable
- Low cost compared to conventional test equipment

These specifications guarantee that OPM modules and measurement concepts implemented into optical networks are cost-efficient, flexible and well suited regarding measurement tasks, performance and operational effort.

5. ADVANCED OPM TECHNOLOGIES

After having identified different tasks of OPM and after having discussed the required key measurement features we will consider different advanced technologies. This is of special interest since as shown above future networks will comprise new functionalities. These in turn will lead to new failures which have to be detected fast and reliably. In the following, the most promising approaches which are not already in use will be considered.

5.1. Polarization measurements

In order to measure real in-channel OSNR values, one can utilize the different polarization characteristics of optical signals and of optical noise [8-16]. To a first approximation, one can assume that an optical signal is completely polarized whereas noise contributions are completely non-polarized. Thus, by measuring the degree of polarization (DOP) one can determine the optical noise level.

One approach to measure the DOP is to utilize a spectral polarimeter which measures all three components of the Stokes vector (s1, s2, s3) as a function of wavelength. By this concept spectral polarimeters can also estimate the PMD. Another approach to determine the DOP is called Polarization-Nulling (Pol.-nulling). Here, two photodiodes are placed at the exits of a polarization beam splitter (PBS). A polarization controller in front of the PBS is set in such a manner that the intensity at one photodiode is minimized (cf. Fig 6). By this procedure one makes sure that nearly the complete power of the data signal is launched onto the second photodiode whereas the first photodiode measures only noise contributions.

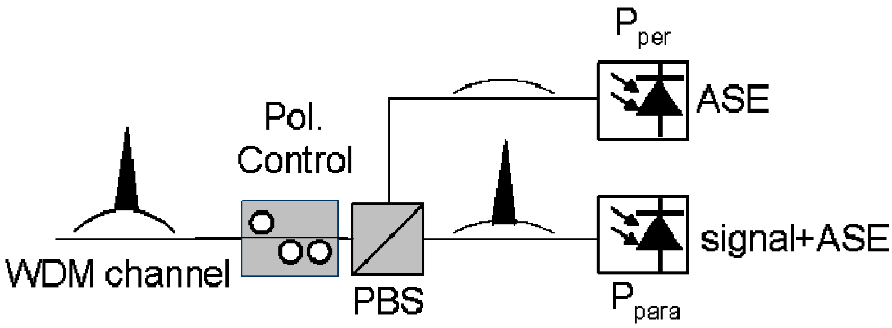

Fig. 6: Principle polarization-nulling setup to measure the OSNR of a DWDM channel.

One technical problem of DOP measurements is to make sure that the state of polarization (SOP) is stable during the measurements. Moreover, the optical signal depolarizes due to PMD and to nonlinear birefringence. In this case the SOP becomes frequency dependent. Possible solutions are to implement PMD compensating techniques to cancel out such disturbing effects or to make recourse to differential detection schemes. This however increases control effort and thus drives module costs.

As stressed above, fiber non-linearities can also significantly change the polarization properties of the optical signal. For instance, neighboring channels can introduce time-dependent birefringence and by this, fast polarization changes on a bit level. This strongly disturbs DOP measurements. Further, FWM can significantly alter DOP measurements as the additional signal is well polarized. The FWM signal can be split into fractions parallel and perpendicular to the signal.

The parallel fraction adds up to the signal power and would thus increase the OSNR. In contrast to that the fraction perpendicular to the signal would add to the noise level and thus decrease the OSNR. In both cases FWM falsifies measurements of polarization properties of optical signals and OSNR measurements.

In summary the advantages of DOP measurements are

- Real in-channel OSNR measurements
- Principally fast measurements
- Multi-channel operation
- Low input power operation
- Data rate and modulation format transparency
- Potentially low costs
- Can principally also measure PMD

Disadvantages are

- Impairments due to polarization rotation
- Impairments due to PMD
- Impairments due to depolarization by fiber non-linearities

Polarization measurements may show up as attractive and cost efficient alternatives to OSAs and have become commercially available. However, this method is less transparent to modulation formats and data rates than the classical OSNR monitoring by OSAs. Nevertheless it provides the real in-channel OSNR.

5.2. Electrical and optical amplitude sampling (EAS/OAS)

Electrical or optical amplitude sampling is a suitable way to derive the in-channel OSNR [17-26]. Here the power levels of the bits of an incoming data stream are sampled. The sampling window is usually short compared to the bit duration. The measured amplitude histogram displays the probability density distributions of the sent marks and spaces. From the positions and width of the distributions of marks and spaces one can calculate the OSNR and Q factor. The sampling is either carried out electrically (for sampling windows > 3 ps) or optically when very short sampling pulses (< 1 ps) or high sampling rates (> several MHz) are needed. Fig. 7a displays amplitude histograms resulting from measurements carried out for an optical 10 GHz NRZ signal in presence of optical noise.

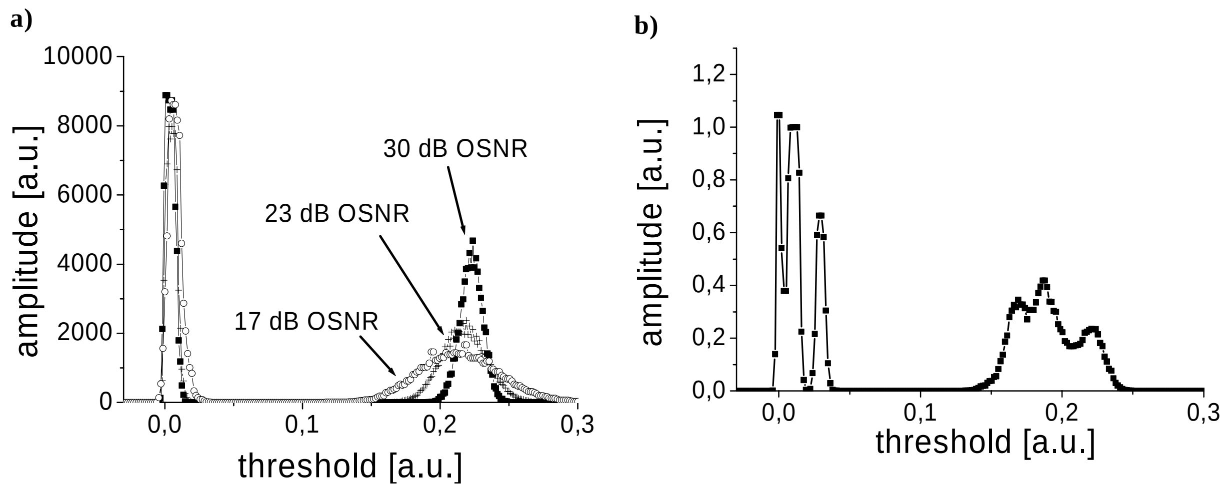

Fig. 7: EAS histograms of optical 10 GHz NRZ signals in presence of optical noise (a) and in presence of chromatic dispersion (b).

Fig. 7a displays amplitude histograms resulting from measurements carried out at optical 10 Gbit/s signals at OSNR levels of 30, 23, and 17 dB. Fig. 7b shows the distorted amplitude histogram of the same 10 Gbit/s channel in presence of chromatic dispersion.

The overall advantage of EAS/OAS measurement techniques is that due to direct conversion of optical signals into interpretable measurement, data amplitude sampling is very closely related to the optical signal quality. EAS/OAS measures the real in-channel noise level. However, not only amplifier noise but also other signal quality degrading effects, which change the eye diagram, contribute to the recorded amplitude histograms. Besides amplifier noise, there are two more classes of effects which can be recognized. The first class comprises noise-like effects resulting from multi-channel crosstalk e.g. FWM, Stimulated Raman Scattering (SRS), and XPM. They behave noise-like as the disturbing conditions between interacting channels are random and unknown. In this case signal quality can still be well estimated (cf. Fig 8).The second class comprises signal distortions e.g. SPM, chromatic dispersion, or PMD. These effects distort the form of the amplitude histogram (cf. Fig. 7b). In such cases estimation of signal quality is hardly possible.

The drawback of amplitude sampling is the technical effort which has to be taken. For amplitude histograms of a good quality, one needs a fast photodiode (B_{el} > data rate), an amplifier to realize sufficiently high input powers and a high-speed sampling oscilloscope. This equipment drives costs. Thus currently such investments are only feasible for lab experiments. To summarize one can identify the following advantages

- Real in-channel OSNR measurements
- Data rate and modulation format transparency
- Measurements include all disturbing effects

On the other hand following disadvantages exist

- Currently very expensive technology
- No existing component-level solution
- Ambiguous results → need for further analysis
- High input power necessary

In summary EAS/OSA are principally well suited for OPM. But high technical effort and related costs make its implementation in future networks questionable.

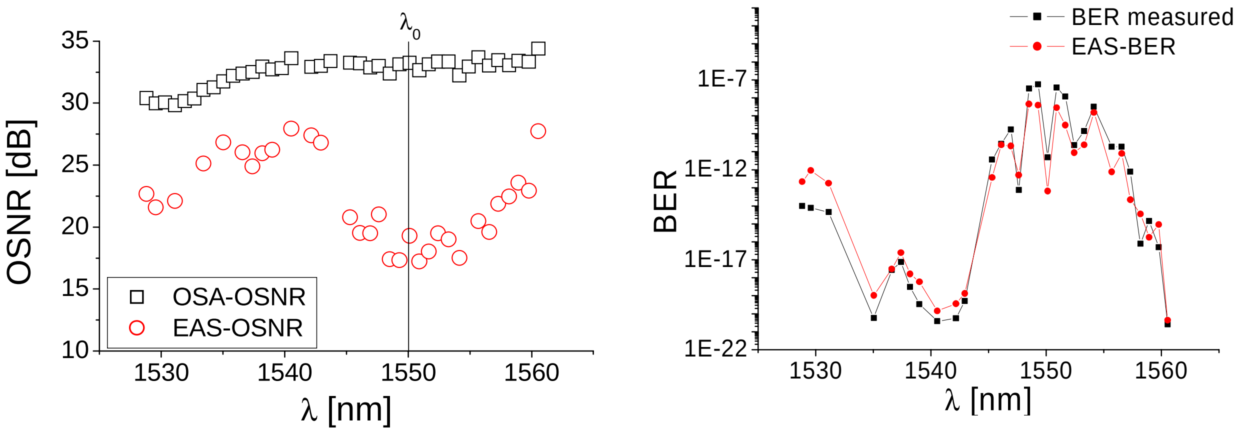

Fig. 8: OSNR values derived from EAS and OSA measurements (a) and comparison of BER measured by a BERT and derived from EAS measurements (b) in presence of strong FWM.

5.3. BER measurements

The BER is the ultimate parameter to describe the optical signal quality and to check network performance. It can efficiently assure provided service and network's availability to customers and can therefore be used for SLA supervision. The use and benefit of BER measurements for in-line OPM has been widely discussed. On one hand, the BER is sensitive to every kind of signal-disturbing effect and consequently measures any signal degradation. On the other hand, BER is just one parameter, which is influenced by every kind of disturbing effect, and this parameter alone cannot distinguish between different root causes for signal degradation. So, although the BER is always promoted as a key quality of service parameter, the BER has only limited significance for the objective of root cause analysis.

Another issue is that although at the termination point one gets the channel BER for free in-line BER measurements require high effort. An optical filter has to select the channel out of the WDM comb first. Than optical amplifiers are required as only a small fraction of power is available for BER measurement. A tunable dispersion-compensator (TDC) has to compensate for local dispersion. Fig. 9 sketches a respective setup for in-line BER measurements.

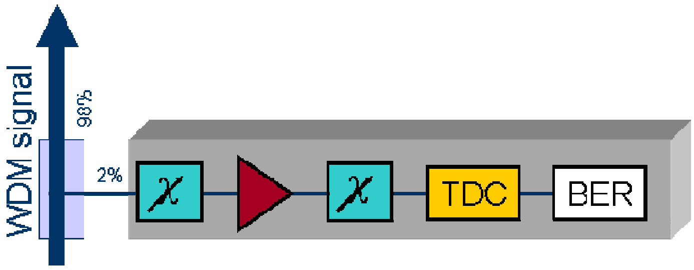

Fig. 9: Setup to implement receiver based BER measurements comprising channel selector, amplifier and tunable dispersion compensation.

Today two techniques exist to measure the BER in-service. The fist one bases on counting bits corrected by a FEC [27,28]. Advantages are

- True BER
- Well-known technology
- Fast measurement (1 s)

Disadvantages are

- Need of additional hardware
- Not effect specific / no statement about root cause
- Data rate, modulation format, and FEC-code dependent
- Applicable only to medium signal quality (10^{-9} < BER < 10^{-5})

The second approach estimates BERs on the basis of Q-factor measurements utilizing receivers with variable decision circuits [29-31]. Here the threshold of the second decision circuit is varied whereas the first decision circuit is kept fixed and used as reference. Both decision processes are compared and different results are interpreted as errors. These errors are plotted as function of the variable decision threshold. By fitting measured data with Gaussian distributions one can derive the channel's BER, see Fig. 10.

This procedure however implies that the signal is disturbed by noise-like effects, while it fails in presence of distortions. Further, because this procedure counts real bit errors, measurement times can be up to minutes.

Advantages of this technique are

- Good BER estimation

Disadvantages are

- Need of additional hardware
- Not effect specific / no statement about root cause
- Data rate / transmitter, modulation format dependent
- Slow measurement

In summary, BER measurements seem not really useful for in-line OPM due to the high costs and low significance of respective results. Further they provide only limited significance when used to determine the failure root cause, e.g. signal distortions or optical noise.

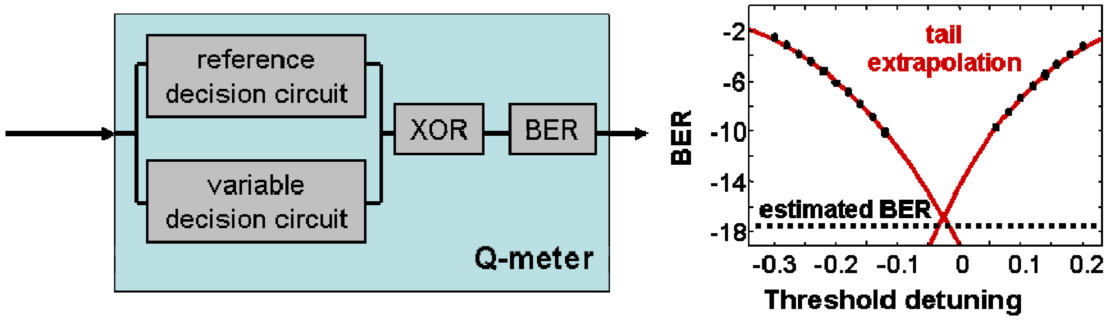

Fig. 10: Q-Meter scheme (a) and channel BER evaluation (b).

5.4. Distortion identification based on equalizer coefficients

Recently, investigations have been carried out to assess and investigate the possibility to analyze coefficients of adaptive equalizers in order to determine causes of signal distortions [32,33]. It has been demonstrated that filter coefficients of electrical adaptive equalizer provide information about the mitigated distortion. The setup of an electrical feed forward equalizer (FFE) with five taps and the filter coefficients in presence of chromatic dispersion is depicted in fig. 11.

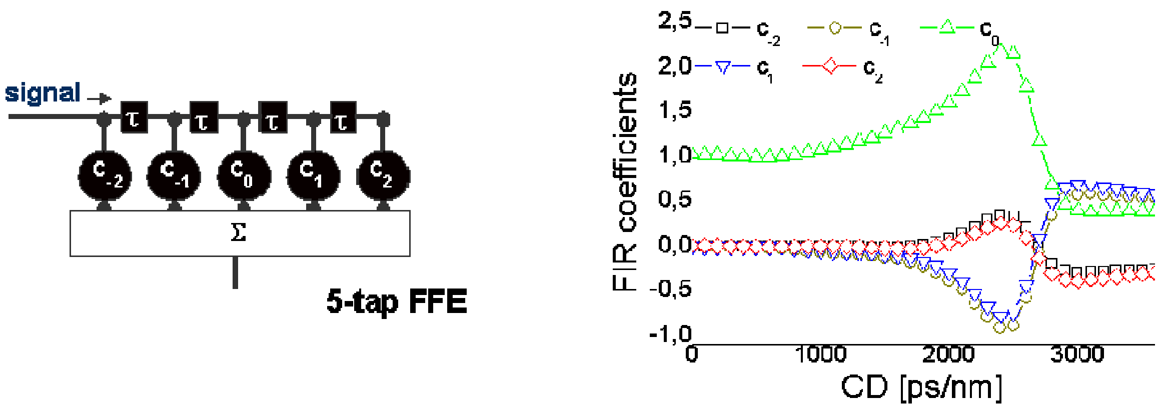

Fig. 11: Structure of an FFE comprising five taps (left) and respective filter coefficients as function of set dispersion (right).

The systematic variation of the filter coefficients can be used to estimate kind and magnitude of the pressent distortion. The method should work even better in case of optical compensators. Here in contrast to electrical equalizers, where a photo diode converts the optical signal into the electrical domain by, the phase information is preserved.

General advantages of this method is its

- Cost-effective when used at receiver site
- No additional hardware
- Direct identification of signal distortions
- May be used to insert small distortions to study changes of signal quality

A major disadvantage is that this novel method has to be investigated further before implementing it into real systems. However this method provides interesting possibilities since in future receivers compensators will most probably be integrated anyway. Thus, this additional information will be come for free.

6. SUMMARY

In summary this paper has considered future optically transparent DWM networks. With respect to OPM different consequences resulting from such flexible dynamic networks have been described. Typical network failure scenarios have been discussed. To identify and localize alarm root causes in such networks the advantages of data correlation have been described. It was shown that failure root cause analysis based on alarm correlation can increase network reliability and minimize the hardware effort necessary for OPM. Finally, strength and weaknesses of different advanced OPM techniques were reviewed. It turns out that in many cases the technical and monetary effort for embedding such OPM devices into the system is significant. Thus to choose the optimal OPM hardware to be implemented into the systems it is essential to precisely define the exact tasks and the expected results of OPM in order to optimize the benefits-costs relation.

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