Impairment Identification in an Optical Transparent Network Using OFDM Transmission

Markus Mayrock, Herbert Haunstein
Institute for Information Transmission, Friedrich-Alexander University Erlangen-Nuremberg
Cauerstr. 7/LIT, D-91058 Erlangen, E-Mail: {mayrock | haunstein}@LNT.de

Abstract

Monitoring of optical transmission impairments is achieved by signal processing at the receiver. In an OFDM system spectral properties can be extracted for this purpose in particular. The proposed method, which allows separation of linear and non-linear impairments, is applied in simulation to monitor a number of paths in a small test network.

1 Introduction

Recently, there is increasing interest in coherent detection systems and orthogonal frequency division multiplexing (OFDM). A couple of OFDM system architectures have been investigated in simulations and experiments [1],[2],[3],[4]. Besides robustness to highly dispersive channels, OFDM inherently delivers monitoring capabilities. Chromatic dispersion and OSNR can be estimated by analysis of the received symbols and sub-channel coefficients [5]. An extension of this monitoring method allows for the separation of linear and non-linear distortions and other noise sources [6].

In this contribution we examine the performance of this approach when it is applied to a simple network scenario. For this purpose we define an exemplary network topology and apply routing and wave-length assignment to determine a set of paths which covers a given traffic matrix. These paths exhibit different amounts of chromatic dispersion, differential group delay, additive noise, and distortions due to fiber non-linearity.

The proposed method utilizes the channel estimates generated at the receiver to calculate a linear frequency response of the optical transmission channel. All orthogonal received power is interpreted as noise. Applying two sets of spectral estimates, the ASE noise contribution can be distinguished from the "non-linear noise" part [6].

To demonstrate the concept a set of paths through a simple network is simulated and the link properties are estimated. Finally, the problem of impairment localization is addressed.

2 Monitoring based on OFDM channel estimation

The proposed monitoring method is based on a system identification approach: A weakly non-linear system can be described by a parallel concatenation of a linear system and an unknown non-linear block which generates an additive, noise-like signal. One can estimate the linear transfer function and the power spectral density of the noise-like distortion with the help of spectra of transmit and received sequences. The application of this technique to an OFDM system is straightforward. At the OFDM transmitter a number of modulated symbols is fed to an inverse discrete Fourier transform (IDFT) before further processing and transmission. At the receiver the signal is sampled and given to DFT computation. Therefore the Q sub-carriers of OFDM symbols actually represent sampled spectra of the TX and RX signals. We obtain orthogonal narrowband sub-carriers which can be modeled as depicted in Figure 1.

![Figure 1: Transmission model for a single sub-carrier.](image)

**Figure 1: Transmission model for a single sub-carrier.**

Estimation of the transfer function maps to the following sub-channel based operation

\[ H(d) = \frac{E\{|Y(d)\cdot X^*(d)|\}}{E\{|X(d)|^2\}}, \quad d = 1, Q. \]  

(1)

The power spectral density of the additive distortion, which comprises additive noise and the noise-like distortion due to fiber non-linearity is obtained by
\[ \Phi_{\text{sn}}(d) = E\left\{ |Y(d) - H(d) \cdot X(d)|^2 \right\} \]  
(2)

In the following, we analyze mean signal powers rather than spectral power densities. The integration over the used frequency band is accomplished by the summation over the discrete sub-carriers \( d \):

\[ \frac{N}{S} = \frac{\sum_{d=1}^{Q} \Phi_{\text{sn}}(d)}{\sum_{d=1}^{Q} |H(d) \cdot X(d)|^2} \]  
(3)

This equation describes an inverse signal to noise power ratio which adds up from the two mentioned contributions (assuming statistical independence)

\[ \frac{N}{S} = \frac{N_{\text{ASE}} + N_{\text{nl}}}{S} \]

In the purely linear regime the relative distortion decays by one dB when the input power is increased by one dB. For higher optical powers the distortion is dominated by non-linearity; in this region the relative distortion increases by about 4 dB per 2 dB optical power increment [6] due to self-phase modulation. Therefore, both contributions can be separated with the help of two measurements at distinct power levels. At an unknown OSNR we at first estimate

\[ m_1 = \frac{N_{\text{ASE}}}{S} + \frac{N_{\text{nl}}}{S} \]

Then the optical input power is increased by 10\( \log(k) \) dB which results in a second estimate

\[ m_2 = \frac{N_2}{kS} = \frac{N_{\text{ASE}}}{kS} + \frac{k^2 N_{\text{nl}}}{S} \]

according to above mentioned observations. From these measurements we can extract the wanted ratios \( N_{\text{nl}}/S \) and \( N_{\text{ASE}}/S \):

\[ \frac{N_{\text{nl}}}{S} = \frac{km_2 - m_1}{k^3 - 1}, \quad \frac{N_{\text{ASE}}}{S} = \frac{m_1 - N_{\text{nl}}}{S} \]  
(4)

Linear distortions can be extracted from the estimated transfer function. Chromatic dispersion solely influences the phase response of \( H(d) \), whereas DGD has impact on its magnitude [7].

3 Exemplary network scenario

We investigate a simple 6-node meshed network as depicted in Figure 2 with the given link lengths (kilometers). Standard single mode fiber is considered (constant dispersion coefficient of 17 ps/(nm km) for wavelengths around 1550 nm). All the links do not have any dispersion compensation.

Next we arbitrarily choose a traffic demand matrix as summarized in Table 1. This demand matrix is mapped to transmission paths with the help of a routing and wavelength assignment algorithm, which is not subject to optimization at this point. It works basically according to the rules given in [8].

<table>
<thead>
<tr>
<th>From node</th>
<th>To node</th>
<th>Bitrate [Gb/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 1: Traffic demand.

For each path a 20 Gb/s OFDM system shall be applied. For our simulations we set up systems based on coherent detection, \( Q = 128 \) sub-carriers, 16QAM modulation, and a cyclic prefix length of 12.5%. The estimation procedure described in equations (3) and (4) is carried out with the help of 10 preamble symbols. The resulting light paths are listed in Table 2.

<table>
<thead>
<tr>
<th>Path no.</th>
<th>Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 – 5 – 3 – 4</td>
</tr>
<tr>
<td>2</td>
<td>1 – 3 – 6 – 4</td>
</tr>
<tr>
<td>3</td>
<td>1 – 2 – 4</td>
</tr>
<tr>
<td>4</td>
<td>1 – 5</td>
</tr>
<tr>
<td>5</td>
<td>1 – 3 – 5</td>
</tr>
<tr>
<td>6</td>
<td>1 – 5 – 3 – 4 – 6</td>
</tr>
<tr>
<td>7</td>
<td>1 – 3 – 6</td>
</tr>
</tbody>
</table>

Table 2: Selected light paths.

4 Simulations

The sample network used here is assumed to have negligible PMD. However, the method can be extended for the case of polarization multiplexing along with polarization diversity detection, as described in [9]. Then the channel estimation process delivers the transfer functions of a 2x2-MIMO-system. Their entries for each sub-carrier correspond to a Jones matrix which determines the PMD characteristic of the fiber within the used frequency band.
Chromatic dispersion generates a parabolic phase characteristic around the carrier frequency:

\[
H(f) = \exp \left( j \pi \cdot DL \frac{f^2}{c} \right),
\]

with \( \lambda \) and \( c \) denoting the wavelength and the speed of light. However, at the presence of other linear distortion the overall phase response equals a shifted parabola. The estimates for the phase \( \phi(d) \) of the sub-carrier coefficients \( H(d) \) generate an over-determined set of equations:

\[
\phi(d) = \alpha \cdot d^2 + \beta \cdot d + \gamma, \quad d = 1, Q
\]

Usage of quadratic regression gives an estimate for the parabola parameter \( \alpha \), which in turn lets us determine the accumulated chromatic dispersion \( DL \):

\[
DL = \frac{\alpha \cdot c}{\pi^2 \cdot \Delta f^2}, \quad (5)
\]

where \( \Delta f \) denotes the sub-carrier bandwidth. Figure 3 visualizes an exemplary set of estimated phases along with the regression parabola.

When we apply this method to extract the accumulated chromatic dispersion from the linear transfer function to the set of light paths, we obtain estimates as displayed in Figure 4. For comparison it shows the true path dispersions which are known from the network architecture along with the information how the paths are routed through the network.

In order to visualize the gap between actual and estimated values the relative error is shown. It stays below 4%; just path no. 5 exhibits a higher estimation error of approximately 9% which may be caused by the fact that this channel is operated at higher optical power (see following section).

**Fiber non-linearity**

In a next step the same recorded data and the estimated linear transfer function is used for calculation of the inverse signal to noise power ratio according to (3). Optical signal powers have been set as shown in Table 3. A second estimation process is started after optical power increment of 1 dB. Now we can separate the distortion due to self-phase modulation from additive noise for each path in the transparent network. The results are summarized in Figure 5.

<table>
<thead>
<tr>
<th>Path no.</th>
<th>opt. power ([\text{dBm}])</th>
<th>OSNR ([\text{dB}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>21.6</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>18.7</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>17.7</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>30.0</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>24.5</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>20.3</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>18.9</td>
</tr>
</tbody>
</table>

**Table 3: Optical path parameters.**

The results are summarized in Figure 5.

![Figure 4: True and estimated residual chromatic dispersion and relative error.](image)

![Figure 5: Relative powers of signal distortions.](image)
We observe that paths 4 and 5 are mainly impaired by distortion due to fiber non-linearity. It should be mentioned that the simulation currently does not include cross-phase modulation between WDM channels.

5 Localization of impairments

The presented monitoring method is based on channel estimation within an optical OFDM system. Thus, it operates between end-terminals and gives information about the total path through the transparent network. After setting up paths this method allows for validation of the impairments which we have to expect because of the network design. During operation the monitoring algorithm shall track and identify unexpected impairments.

A further important task of monitoring is localization of unexpected impairments. The monitoring results at the receiver cannot directly tell at which exact position there is a deviation from normal operation. To approach this problem we can make use of correlations between WDM channels and the knowledge about the architecture and routing.

As a first example we give 1000 ps/nm of additional chromatic dispersion to the link between nodes 3 and 6 (this rather high value is chosen for demonstration purposes). After dispersion monitoring we obtain values as given in Figure 6. Obviously except for paths 2 and 7, the monitored measures of chromatic dispersion agree well with the expected ones. Having a look at the routing table gives us the hint that the additional dispersion must be located between nodes 1 – 3 – 6.

For a formal determination of the link dispersions we define:

\[ DL_{p,q} \]: chromatic dispersion between node \( p \) and \( q \) (to be estimated)

\[ DL_{est,i} \]: estimated dispersion for path \( i \).

For paths 1 and 6 we can state:

\[ DL_{1,5} + DL_{3,4} + DL_{4,6} = DL_{est,1} \]

\[ DL_{1,5} + DL_{2,3} + DL_{3,4} + DL_{4,6} = DL_{est,6} \]

Zero dispersion slope is assumed here (a known dispersion slope could be considered as the paths’ wavelengths are known). If we assume a single location of unexpected impairment we can set all the values \( DL_{p,q} \) which are not affected by paths 1 and 6 to the values which are known from the network architecture. Especially \( DL_{1,5} \) now is known. \( DL_{4,6} \) can be calculated through the difference between both equations:

\[ DL_{4,6} = DL_{est,6} - DL_{est,1} = 450 \, \text{ps/nm} ,\]

which is near to the designed measure. Consequently the impairment is located between nodes 5 – 3 – 4. More detailed localization is not possible with the available information.

6 Conclusions

Optical parameter monitoring has been applied in an OFDM receiver, which provides spectral estimates for the linear transfer function and an uncorrelated noise power spectrum. The concept allows for separation of transmission impairments. Combined information from multiple paths (at different end terminals) shall enable localization of impairments, which is subject to further studies.

Acknowledgement

This work is funded in part by the German Ministry for Research and Education (BMBF Grant MUNAS 01BP554, under sub-contract with Alcatel-Lucent Deutschland AG).
Literature


