CHARACTERIZATION OF PHYSICAL LAYER IMPAIRMENTS IMPACT ON OPTICAL FIBER TRANSMISSION SYSTEMS

Suhail Al-Awis and Ali Y. Fattah
Department of Communications Engineering, Faculty of Electrical Engineering
University of Technology, Baghdad, Iraq

ABSTRACT

In this paper the characterization of the impact of physical layer impairments on quality of transmission of optical fiber transmission systems had been demonstrated analytically and verified numerically with simulation results. Linear and nonlinear impairments in optical links accurately characterized with analytical modeling techniques but on the counterpart it is cost efficient to characterize the impact of these impairments using empirical techniques which provides real time information of these impairments to digital signal processing algorithms used in their compensation to ensure high throughput of the optical transmission systems.

Keyword: Optical Fiber, Characterization, Physical Layer Impairments and Quality of Transmission.


1. INTRODUCTION

The quality of transmission of high speed optical fiber transmission systems is highly affected by chromatic dispersion (CD), phase noise (PN), polarization mode dispersion (PMD) and nonlinear effects. Coherent optical detection allows the significant equalization of transmission system impairments in the electrical domain, and has become one of the most promising techniques for the next generation communication networks. With the full optical wave information, the fiber dispersion, carrier phase noise and the nonlinear effects can be well compensated by the powerful digital signal processing (DSP) [1].
Extensive addressing of the coherent optical transmission systems in the eighties of the last century was resulted due to highly sensitive receivers [2,3]. However, 20 years later coherent technologies has been delayed [4-6]. Higher order modulation formats detected by coherent detection like PDM-QPSK, PDM-8PSK, PDM-8QAM, PDM-16QAM and PDM-36QAM use all possible degree of freedom of the optical wave for information encoding via IQ-modulators to access in-phase and quadrature-phase components for both polarizations to best utilize the available bandwidth more than binary alternatives and boost the capacity without the installation of any extra fibers [7-13]. Efficient modulation formats such PSK and QAM which are implemented with the aid of DSP receivers attracted the interests of investigation until 2005 [14]. Electronic compensation of the transmission impairments as powerful as traditional optical techniques was enabled by fully accessing the optical wave information [6].

Canonical model of a multi span long haul optical fiber transmission system is shown in Figure 1 (a). Before the invention of the optical amplifiers, optical-electrical-optical (O-E-O) conversion take place to compensate the channel impairments and the electrical signal is re-amplified, re-shaped, and re-timed (3R regeneration) before converted back to optical format. O-E-O conversion is expensive and requires priori knowledge of the transmitted signal such as its symbol rate at the repeater in order to perform 3R regeneration [15].

Figure 1 (a) Canonical model of a multi-span long-haul fiber channel, (b) Multispan long-haul fiber channel with inline amplification and dispersion compensation

Invention of the erbium doped fiber amplifier (EDFA) in the 1990s stalled the development in coherent optical systems, which enabled repeaterless transmission over long-haul distances. The combination of the C-band (1530–1570 nm) and L-band (1570–1610 nm) spectrums resulted in 10 THz of bandwidth. Rapid growth of internet applications traffic, such as multimedia sharing, made this bandwidth becoming rapidly fully utilized. Thus, there is renewed interest in high-spectral-efficiency transmission over long distances [16].

New challenges ahead the new channel configuration, in which optical signals are propagated over thousands of kilometers of fiber, such as the need to compensate chromatic dispersion (CD). A typical long-haul system model is shown in Figure 1 (b), with inline amplification and dispersion compensation fiber (DCF) after every span. Furthermore, as the number of wavelength division multiplexed (WDM) channels per fiber increase, and as the data rate per channel increase, fiber nonlinearity, (PMD) and other impairments which were previously not important became limiting factors [15]. Transmission impairments in optical fiber communication can be categorized into linear and nonlinear impairments. Linear
impairments include attenuation, amplified spontaneous emission (ASE) noise, polarization mode dispersion (PMD), chromatic dispersion (CD) and linear crosstalk in WDM systems from optical de-multiplexers/ filters and wavelength routers. On the other hand self-phase modulation, cross-phase modulation, cross polarization modulation classified as nonlinear impairments. To understand these impairments, the propagation of a pulse in an optical fiber channel which is described by nonlinear Schrödinger equation [17] should be understood clearly:

\[
\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial T^2} = i\gamma |A|^2 A
\]

(1)

Where \(A\) is the signal amplitude, \(z\) is the distance of the fiber, \(\alpha\) is the attenuation coefficient, \(\beta_2\) is the group velocity dispersion parameter and \(\gamma\) is the Kerr nonlinear coefficient.

2. THEORETICAL BACKGROUND

2.1 Linear Impairments

Modelling of single mode fiber in the absence of the nonlinearity can be considered as linear time invariant (LTI) channel with dually polarized inputs and output as shown in Figure 2 [15].

**Figure 2** Dual-polarization linear channel modelling

The channel can be characterized by its impulse response matrix as shown in equation 2.

\[
h(t) = \begin{bmatrix} h_{11}(t) & h_{12}(t) \\ h_{21}(t) & h_{22}(t) \end{bmatrix} \quad \mathcal{F} \quad H(\omega) = \begin{bmatrix} H_{11}(\omega) & H_{12}(\omega) \\ H_{21}(\omega) & H_{22}(\omega) \end{bmatrix}
\]

(2)

where \(h_{ij}(t)\) is the response of the \(i\)-th output polarization due to an applied impulse at the \(j\)-th input polarization of the fiber. \(H(\omega)\) and \(h(t)\) are Jones matrices with frequency-dependent and time-dependent elements, respectively. The matrix description of the channel is sufficient for describing CD, polarization-dependent loss (PDL), all PMD orders, optical filtering effects, sampling time error, and any other linear impairment [18].

2.1.1 Fiber attenuation

Fiber loss parameter \(\alpha(z)\), which describes the attenuation of the optical signal power while propagating through the fiber channel as shown in equation (3).

\[
\alpha(z) = -\frac{10}{z} \log_{10} \left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)
\]

(3)

Where \(z\) is the length of the fiber channel, \(P_{\text{out}}\) and \(P_{\text{in}}\) are the output and input optical powers of transmission fiber span respectively. It is mainly caused by material absorption and Rayleigh scattering effects, but it is also a function of carrier signal wavelength [19].
2.1.2 Chromatic dispersion

In [17] Linear Schrödinger Equation (LSE) described, where $\beta$ can be expanded around the carrier frequency into a Taylor series approximation, truncated at the 3rd term as in equation (4):

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \beta_1 \frac{\partial A}{\partial t} + i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial t^3} = 0 \quad (4)$$

Here the group velocity $v_G$ is related to $\beta_1$ and therefore calculate the speed the envelope of an optical signal propagates along the fiber:

$$\beta_1 = \frac{1}{v_G} = \frac{1}{c} (n + \omega \frac{dn}{d\omega}) \quad (5)$$

With $c$ is the light speed in vacuum, $n$ is the linear refractive index and $\omega$ is the optical frequency. $\beta_2$ is the group-velocity dispersion (GVD) parameter, which broadens the travelling pulse:

$$\beta_2 \frac{1}{c} \left(2 \frac{dn}{d\omega} + \omega \frac{d^2 n}{d\omega^2}\right) \quad (6)$$

D is defined as the dispersion parameter of the first derivative of $\beta_1$ with respect to the optical wavelength $\lambda$:

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2 \approx \frac{\lambda^2n}{cd\lambda^2} \quad (7)$$

$\beta_3 = d\beta_2/d\omega$ is the GVD slope parameter, which relates to the dispersion slope parameter S by:

$$S = \frac{d\beta_2}{d\lambda} = -\frac{4\pi c^2}{\lambda^3} \beta_2 + \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 \quad (8)$$

At the zero dispersion wavelength ($\beta_2 = 0$) region, the GVD slope becomes especially important for transmission. The retarded time frame $T = t - z/v_G$ is introduced, which propagates with the signal at the group velocity dropping $\beta_1$ from the equation. Finally, the GVD slope influence can be neglected by considering standard single-mode fibers (SMF) or other types with sufficiently high GVD:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} = 0 \quad (9)$$

The total dispersion profile of an optical fiber can be evaluated by material and waveguide dispersion respectively (DM) and (DW). For the SSMF the summation of these parameters resulted in a dispersion profile shown in Figure 3, with the zero dispersion wavelength at 1324 nm and D=16ps/km/nm at 1550 nm [20].

![Figure 3](http://www.iaeme.com/IJECET/index.asp) Dispersion characteristic of a typical SMF as a function of wavelength and frequency.
2.1.3 **Polarization mode dispersion**

Polarization of a light considers as a property of electromagnetic waves that shows the transverse electric field orientation. X and Y are two orthogonal polarization states exists in SMF. Stokes parameters can be used to describe the representation of light polarization, which expressed straightforward by using Poincaré sphere. This sphere consists of four parameters in terms of optical power as shown in Figure 4 [21].

![Figure 4 Poincaré sphere](image)

SMF supports the transmission of two orthogonal polarization-modes, but temperature fluctuations and random birefringence resulted from mechanical stress changes the states-of-polarization (SOP) and, hence, the GVD to vary with time and along the fiber length [22]. A typical fiber length ranges from hundreds of meters up to few kilometers along which the SOP varies. Mathematically, the modal birefringence, $B_m$ described in equation (10):

$$B_m = \frac{|\beta_x - \beta_y|}{2\pi} = \left|n_x - n_y\right|$$

(10)

Where $n_x$ and $n_y$ as the effective refractive index of both modes. $\beta_x$ and $\beta_y$ are the modes propagation constants. The axis with larger group velocity described as the fast axis while the other with smaller group velocity denoted as the slow axis, referring to Figure 5 for a linearly polarized optical pulse launched at $45^\circ$ into a fiber. The difference between arrival times of the two pulses is referred to as differential group delay $\Delta J$ (DGD) which have Maxwellian distribution around mean DGD-value $\langle \Delta J \rangle$. [20].

![Figure 5 Random birefringence and resulting DGD for optical pulse launched into a fiber at 45° with respect to slow axis.](image)

The PMD-induced pulse broadening can be evaluated from the DGD between the two polarization components after averaging over random birefringence [23] as
\[ \Delta T = D_P \sqrt{L} \]  
(11)

Where \( D_P \) is the fiber PMD parameter measured in ps/\( \sqrt{\text{km}} \). While in [24] PMD power penalty can be estimated as,

\[ \text{pen}_{\text{PMD}} = 10.2B^2D_P^2L \]  
(12)

Where \( B \) as the signal bit rate.

2.1.4 Linear cross talk in WDM systems

It arises in wavelength routers, optical filters and de-multiplexing devices. In WDM systems a signal at a particular wavelength is de-multiplexed at the receiver by means of an optical filter. Wavelength components outside the signal optical bandwidth is not completely suppressed by the optical filters. Thus power from adjacent channels in a WDM system leaks into the central channel causing what is known as a cross talk penalty in the central channel. This penalty increases as the number of multiplexed WDM channels is increasing. It is called out of band cross talk since this crosstalk is generated by out of bandwidth of the central channel band. Linear out of band crosstalk is shown in Figure 6 [25]. For a WDM system with \( N \) channels the total generated photocurrent by the optical signal filtered at the receiver is given by [20]

\[ I = R_m P_m + \sum_{n \neq m} R_n T_{mn} P_n \equiv I_{\text{ch}} + I_X \]  
(13)

where \( P_m \) is the power of the \( m \)th channel or the filtered channel, \( P_n \) is the power of the \( n \)th neighboring channel, and \( R \) are the receiver photo responsivities and \( T \) is the receiver transmissivity of the \( n \)th channel when the \( m \)th channel is filtered. The current due to the filtered channel power \( (I_{\text{ch}}) \) and the current due to power of the crosstalk from the neighboring channels is \( (I_X) \). The current must be increases by to keep the performance of the system in terms of eye opening.

![Figure 6 Linear cross talk in WDM systems](image)

The power penalty is thus given by

\[ \delta_X = \frac{I_{\text{ch}}+I_X}{I_X} = 1 + \frac{I_{\text{ch}}}{I_X} \]  
(14)

\( \delta_X \) is a measure of out of band crosstalk. Another source of crosstalk penalty in WDM systems which is the wavelength routers based on AWGs. The operation of a 4x4 AWG router is depicted in Figure 7.
Characterization of Physical Layer Impairments Impact on Optical Fiber Transmission Systems

Figure 7 4x4 AWG Router

Where letters a,b,c and d refer to the port and the subscripts 1,2,3 and 4 refer to the wavelength number. For ideal conditions the wavelengths at the input ports are routed to the output ports according to the scheme shown in Figure 7. However due to imperfections in the AWG structure each wavelength in the output port suffers from in band crosstalk which appears due to power leaking from other ports at the same wavelength and the out of band crosstalk which appears from the wavelength channels in the same port [25]. The in-band crosstalk penalty for a WDM system with N channels is given by [26] as shown in equation (15).

\[ \delta_X = -10 \log_{10}(1 - r_X^2 Q^2) \]  (15)

Where

\[ r_X^2 = \chi(N - 1) \]

N is the number of channels and \( r \)-value is the measure of eye opening of the receiver.

2.2. Non-Linear Impairments

Any dielectric subjected to light have nonlinear response for intense electromagnetic fields, and hence the optical fibers. Although the silica is intrinsic and not a highly nonlinear material, but the waveguide geometry that confines light into a small cross sectional area over long haul fiber makes nonlinear effects very important in the design step of modern lightwave systems [27].

Fiber nonlinearities classified either to nonlinear refractive index (Kerr effect) or to nonlinear optical scattering .The Kerr effect take place in response to the dependence of the index of refraction on light intensity. Fiber nonlinearities of this type are self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). The stimulated scattering effects are caused by parametric interaction between the light and materials.

There are two types of stimulated scattering effects: Stimulated Raman Scattering (SRS) and stimulated Brillouin scattering (SBS). One difference between the scattering effect and the Kerr effect is that, stimulated scattering has threshold power level at which the nonlinear effects manifest themselves while Kerr effect does not have such threshold [28].

Assuming that the SOP of the transmitted light is not maintained, it may be shown that the threshold power PB due to Stimulated Brillouin scattering (SBS) is given as in equation (16). While that resulted from the Stimulated Raman scattering (SRS) is given in equation (17) [30].

\[ P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} v \]  (watts)  (16)
Where $d$ as the fiber core diameter and $\lambda$ as the operating wavelength, both are measured in $\mu$m, $\alpha_{dB}$ is the fiber attenuation in dB per kilometer and $v$ is the source bandwidth in GHz.

\[
P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \quad \text{(watts)}
\]

(17)

Where $d$, $\lambda$ and $\alpha_{dB}$ are defined as in equation (16) above.

Decomposing the optical field $A$ in equation (9) into three field components interacting with each other $A_0$, $A_1$ and $A_2$, each describes different WDM channel with $\Delta \beta$ as the phase relationship between them. To highlight the influence of nonlinearity restricted to small-signal distortions, equation (9) can be separated into three coupled equations for WDM channel $A_0$ [29]:

\[
\frac{\partial A_0}{\partial z} + \frac{\alpha}{2} A_0 + i \frac{\beta_2}{2} \frac{\partial^2 A_0}{\partial T^2} = i \gamma |A_1|^2 A_0 + 2 i \gamma (|A_1|^2 + |A_2|^2) A_0 + i \gamma \sum_{l,m \neq 0} A_l A_m^* A_{l+m} e^{i \Delta \beta z} \]

\[
\text{SPM, XPM, FWM}
\]

3. SYSTEM MODEL AND SIMULATION RESULTS

3.1. Linear Impairments Characterization

3.1.1 Chromatic dispersion penalty measurements

The system model depicted in Figure 8, was developed in VPITransmission maker to measure the impact of fiber dispersion for different alfa values of MZM on the BER OSNR and OSNR penalty, which is defined as the difference in optical SNR that is required to reach a certain target BER for the case of propagation over the system of 1 km under test and the back-to-back one. Linear interpolation is used to find the correct OSNR values. The OSNR is varied by adjusting the signal power and keeping the noise power constant. For this approach to work accurately enough, it is critical to set the two attenuation values of the variable optical attenuator in front of the receiver such that the target BER lays in between the two calculated BER values as shown in figure. Simulation results that shows the effect of the OSNR on the BER for different valued of MZM alfa factor which described the chirping behavior of the modulator and the OSNR penalty for different values of dispersion is shown in Figure 9 (a) and (b) respectively.

![Figure 8 System model for OSNR penalty measurements due to fiber dispersion](image-url)

http://www.iaeme.com/IJECET/index.asp  

editor@iaeme.com
Characterization of Physical Layer Impairments Impact on Optical Fiber Transmission Systems

Figure 9 Simulation results for OSNR penalty measurements (a) BER vs OSNR for different values of MZM’s alfa factor (b) OSNR penalty due to fiber dispersion

3.1.2 Polarization mode dispersion penalty measurements

To characterize the effect of the PMD on the optical fiber transmission link, the system model depicted in Figure 10 which is developed with VPITrasmission maker is used for this purpose. It is shown how the SOP of a CW probe signal is changed by the SOP of a CW or modulated pump signal along the fiber. To simplify the simulation, dispersion-less and loss-less fiber with constant birefringence is used with the following settings:

Loops = 20, Fiber Span = 5 km, Attenuation = 0 dB/m, Dispersion = 0 s/m^2.

Figure 10 Three channels WDM system model to identify PMD effects

The Poincare SOP graph is shown in Figure 11 (a) for azimuth 15° and ellipticity of 10° of the CW pump signal. A modification to the SOP of the CW pump signal was made to observe the impact on the probe. Pump SOP changed to azimuth 25°, ellipticity 15° as shown in Figure 11 (b). While in Figure 11 (c) the probe and CW pump have same SOP at azimuth 25°, Ellipticity 15°.
If the CW pump is deactivated and the modulated (10G NRZ) pump is activated, the depolarization of the probe is clearly observed as shown in Figure 12.

3.1.3 Linear cross talk in WDM systems penalty measurements

To illustrate the impact of non-adjacent crosstalk in the NxN AWG on the BER level in such NxN optical interconnection systems. Following the experimental setup in [31], the beat crosstalk for only a single wavelength had been simulated with VPI photonics simulator, using a single signal source divided into 16 paths by 1x16 power splitter as shown in Figure 13 (a). Then one path is used as a source of the main signal, while all the remaining paths are used as sources of same-wavelength crosstalk. All sources are de-correlated from each other by using delay lines with subsequently increasing time delays. After this the rest paths are connected to the AWG's input ports, and the BER is measured for the main signal directed to the AWG's first output port. Eye penalty diagrams for different values of cross talk attenuations are shown in Figure 13 (b-d). Importantly, as is shown in [31], the probability density distribution of the signal-crosstalk beat noise becomes Gaussian at large number of crosstalk sources, N. This allows to employ in the simulation the Gauss method for the BER estimation as shown in Figure 13 (e).
Figure 13 Impact of Crosstalk in an Arrayed-Waveguide Grating Router (AWGR) on NxN Optical Interconnection (a) System Model (b) Eye diag. at 25 dB XT att. (c) Eye diag. at 30 dB XT att. (e) Eye diag. at 35 dB XT att. (d) BER vs ROP for different values of XT att.

Another simulation for a WDM system modelled as in Figure 14 (a) to make a comparison of BER degradations due to intraband and interband crosstalk of the same attenuation level as shown in Figure 14 (b).
3.1.3 Nonlinear impairments penalty measurements

The performance degradation due to Rayleigh and Brillouin scattering can be reduced by separating the frequencies of the counter-propagating channels. In the simulation setup of Figure 16 (a), the crosstalk is represented by the Rayleigh and Brillouin distortions produced in the Universal Fiber. The system performance for different input powers and channels separations is estimated with the Rx_OOK_BER module as shown in Figure 16 (b).

Figure 15 Comparison of BER degradation due to intraband and interband crosstalk of the same level (a) System model (b) BER vs XT attenuation for different cases

Figure 16 Performance degradation due to Rayleigh and Brillouin scattering (a) Simulation Setup (b) BER vs Channel Spacing for Different Channel Power Levels
When pulse collision take place as shown in Figure 17 (b), one pulse walking through a pulse on a different WDM channels the pulses will interact because they both affect the index of the fiber along which they propagated causing XPM impairment as shown in Figure 17 (c). The effect of the fiber's nonlinearity combined with the dispersion of the fiber also causes shaping of a pulse, by its own effect on the fiber's index. This is SPM which will compress a strong pulse, increasing its peak amplitude refer to Figure 17 (d).

Finally the FWM impairment penalty characterization can be clearly observed using VPI Transmission maker simulation setup in Figure 18, which consist of 4 x 10 Gbit/s WDM transmission system over Dispersion Shifted Fiber (DSF). The emergence of the FWM products outside the WDM signal bandwidths can be clearly observed in terms of eye penalty and optical spectrum as shown in Figure 19 (a-b). The WDM signal attenuation due to FWM penalty is shown in Figure 19 (c).

![Figure 17](image1.png)  
**Figure 17** SPM and XPM Measurement (a) Simulation setup (b) Pulse collision of strong and weak pulse (c) Strong pulse impact on weak pulse XPM (d) Weak pulse impact on strong pulse SPM

![Figure 18](image2.png)  
**Figure 18** Simulation Setup of a 4 x 10 Gbit/s WDM transmission system over DSF fiber to characterize the FWM effect
4. CONCLUSIONS

In this paper the physical layer impairments of the optical fiber transmission link had been characterized using analytical modelling and verified using numerical simulations. It is shown that linear impairments are deterministic and have controllable impact on the performance of the transmission links in terms of BER, OSNR and Eye penalty. But nonlinear impairments have nondeterministic and partially controllable impact of the quality of transmission QoT of optical fiber transmission links. Besides the analytical modeling techniques an empirical modelling one which are based on numerical simulations or experimental results seems more promising especially for online impairment measurement and impairment compensation algorithms since empirical techniques will save more computational cost.

REFERENCES


Characterization of Physical Layer Impairments Impact on Optical Fiber Transmission Systems


