Buletin Teknik Elektro dan Informatika
(Bulletin of Electrical Engineering and Informatics)
Vol.2, No.1, March 2013, pp. 45~52
ISSN: 2089-3191

Theoretical Analysis of Backreflections in Bidirectional Wavelength Division Multiplexing-Passive Optical Networks

Joni W. Simatupang
National Taiwan University of Science and Technology (NTUST)-Taiwan Tech
Keelung Rd. Sec. 4, No. 43, Da-an District, Taipei, Taiwan, ROC-106
e-mail: joniwsntust@yahoo.co.id

ABSTRACT

This paper presents the rigorous theoretical analysis of backreflections caused by RB and FR in bidirectional single-fiber single-wavelength transmission over conventional and long-reach WDM-PONs. Conventional WDM-PON takes place in access networks, usually for 20 km transmission distance without node amplification. However, for long-reach WDM-PON which is deployed for 100 km or beyond, optical amplification is indispensable to enhance the optical power budget link and prevent the fiber nonlinearities that happen in the high power level. However, optical amplifier in long-reach WDM-PON might cause the RB and FR effects worse compared with conventional one. It is due to the nature of re-amplification and remodulation feedback of backreflection lights which existed at the preceding and following of optical amplifier or remote node gain.

Keywords: *Backreflections, Bidirectional transmission, Fresnel reflection, Rayleigh bakscattering, WDM-PON.*

1. Introduction

Optical fibers can provide many advantages over other transmission media, such as wireless or copper wires. The huge potential use of optical fibers as a medium transmission to substitute the role of copper wires for many years has been possible due to these following advantages [1]: long distance transmission (lower transmission losses compared to copper wires), large information capacity (have wider/large bandwidths), small size and low weight (over heavy and bulky wire cables), immunity to electrical interference (optical fiber is a dielectric material, which means that it does not conduct electricity like copper wires), enhanced safety (no problems of ground loops, sparks, and potentially high voltages inherent in copper wires), and increased signal security (since the optical signal is well confined within the fiber and an opaque coating around the fiber absorbs any signal emissions). Introducing fibers into access network will remove the bandwidth bottle-neck (last-mile bottleneck) which prevents the development of high-bandwidth interactive consumer devices. However, despite of its remarkable advantages and deployments, optical fibers have some limitations due to its intrinsic nature and external connections with other optical devices. For more than two decades, there was a growing interest in understanding of the effect of Rayleigh backscattering (RB) and Fresnel reflections (FR) since it was known that both of them were limiting factors and important problem as well in various optical communication systems, especially for system architectures which were using only single-fiber single-wavelength (SFSW) for both end directions (bidirectional transmission). In single-fiber loopback access networks, bidirectional transmission of the continuous wave (CW) light and the modulated signal creates a technical issue; the crosstalk-to-signal (C/S) ratio is degraded by the interference intensity noises caused by backreflections in the access fibers. Interference is known as a natural phenomenon in which two waves superimpose to form a resultant wave of greater or lower amplitude. Interference usually refers to the interaction of waves that are correlated or coherent with each other, either because they come from the same source or they have nearly the same frequency. Because the field magnitude is directly proportional to the optical power, interference phenomenon can also be applied to the optical power propagation through medium of fiber optic when optical

Received November 2, 2012; Revised January 18, 2013; Accepted January 29, 2013

signal from the light source at central office (CO) is sent down to the end subscribers at optical network units (ONUs) in wavelength division multiplexing-passive optical networks (WDM-PONs) techniques. The backreflection lights will interfere with the original optical signal and cause the crosstalk problems in network transmission which can degrade the performance of multi-gigabit optical communication system based-on DFB lasers and reflective modulators. Therefore in this paper, we will analyze the systems performance degradations due to the crosstalk from multiple RB and FR in bidirectional SFSW transmission by considering both their effects accurately over conventional and long-reach WDM-PONs. For that reason it is analyzed in more detail afterwards.

This paper is organized as follows. In Section 2, we will compare and show briefly the advantage of bidirectional over unidirectional transmission. In Section 3, the introduction of RB and FR are explained, followed by the description of our schematic modeling. Then, theoretical analysis was derived and discussed. Finally, the conclusion is given in Section 4.

2. Bidirectional Over Unidirectional Transmission

Generally, transmission link is divided into two sections: unidirectional and bidirectional. In the past, the common installed fiber optic systems are unidirectional. It means that the information only travels in one direction down the fiber. A major advantage of this system is that signal impairments caused by the back-reflections from discrete or distributed reflectors can be eliminated by the appropriate use of optical isolators. Optical isolator will eliminate the self-oscillation amplifier to allow the larger gain per stage. Unidirectional systems are primarily limited by amplified spontaneous emission (ASE) and nonlinear effects, such as stimulated Brillouin scattering, stimulated Raman scattering, carrier-induced phase modulation, and four-wave photon mixing during signal transmission.

The main drawback of unidirectional systems is that full duplex communication must occur using a separate fiber cable (dual fibers) or a separate wavelength band (single fiber). Actually it can be argued also from many perspectives, such as hardware efficiency, latency, network integrity and management that bidirectional communication over SFSW transmission is more preferred. It is because in bidirectional signaling, the total aggregate data throughput over a single fiber can be doubled for downstream and upstream traffic occurs at the same wavelength. Single fiber transmission presents a more efficient solution because only half of the amount of fibers is necessary; as well, the cost for connectors, splices, and other network components decrease. Unfortunately, capacity doubling via bidirectional signaling comes with the trade-off that backreflected lights cannot be removed by inline optical isolators, so this system would use optical circulators instead of optical isolators. Therefore, bidirectional network transmission will suffer from two losses contributions which associated with FR from connector facets or fiber splices and RB from fiber in-homogeneities [2].

3. Theoretical Modeling and Analysis

Of main concern of this paper is to analyze the effects RB noise and FR loss in bidirectional SFSW transmission for conventional and long-reach WDM-PON systems. First, we will start with some backgrounds and theoretical basis of RB and FR before going deeper into the theoretical/calculation analysis of their effects in PON transmission systems.

3.1. Rayleigh Backscattering in Single-Mode Optical Fiber

RB was identified as one of the major impairments in low input optical power bidirectional transmissions. In order to prevent damage from this effect, a detailed analysis of its behavior is needed. Actually, for the complete analysis of statistical and spectral properties using correlation functions of the refractive index fluctuations and crosstalk and power penalties of RB in single-mode fibers, readers can refer to some journal papers which were published in early 90's [3], [4], [5], [6], [7], [8].

RB in single-mode fibers is a random deterministic process distribution due to the refractive-index variations arises from the compositional fluctuations during fiber manufacturing. The field distributions in single-mode fibers are well-known to be of nearly Gaussian shape in the radial or circular direction, regardless of the index profile. Two dimensions (2D) fiber model is used as shown in Figure 1 to explain this complex phenomenon.

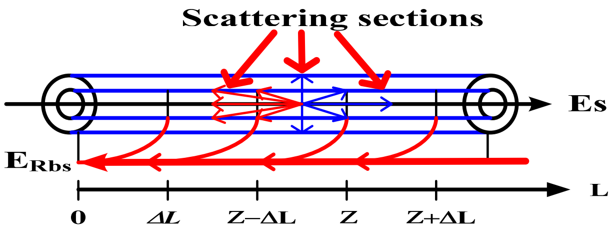

Figure 1. Generic schematic modeling of Rayleigh backscattering in single-mode optical fiber. Some portion of light scattered from each section travel back into original direction and sum up.

A single-mode optical fiber with length L is partitioned into N scatter sections (Ns) where ΔL is equal to L/Ns. Then, a linearly polarized electrical (LPE) field is generated from an optical source such as a DFB laser diode given by its complex amplitude vector:

$$\vec{e}_s(t,z) = \vec{p}_s S_s(t,z) e^{[j\phi(t)]} e^{[j\omega_0 t]}$$

Where, $\vec{p}_s$ is the Jones vector indicates the states of polarization of the field, ω_0 is the optical carrier frequency, and $\phi(t)$ describes the inherent phase noise of the output of the optical source (transmitter). If the fraction of the scattered field from a section located at *z*, which is guided backward, is defined as the backscattering coefficient, $\Delta\rho(z)$, therefore the backscattered signal $\Delta\vec{E}_b(t,z)$ which arrived at the fiber input facet from a scatter section located at z is given by:

$$\Delta\vec{E}_{RB}(t,z) = M(z)\vec{E}_s(t - 2z/v_{gr}) e^{-\alpha z} e^{-2j\beta z} \Delta\rho(z)$$

with α is the intensity attenuation coefficient, β is the propagation constant, v_{gr} is the group velocity, and M(z) is the unitary Jones matrix which describes the round trip change of the polarization state of the electric field propagating through the z axis, $M(z) = P^T(z) * P(z)$.

The total backscattered field is the superposition of the fields contributed from the disjoint scatter sections:

$$\Delta\vec{E}_{RB}(t) = \sum_{n_s=1}^{Ns} \Delta\vec{E}_b(t, n_s\Delta L)$$

By using the differential backscattering coefficient [$\rho(z) = \lim_{\Delta L \to 0} \Delta\rho(z)/\Delta L$], it is possible to calculate the Rayleigh backscattering field at the optical source by integrating (2) over the total fiber length L. It is given by [7]:

$$\vec{E}_{RB}(t) = \int_0^L \vec{E}_s\left(t - \frac{2z}{v_{gr}}\right) \bullet e^{-\left(\frac{\alpha}{2} + j\beta\right)\bullet 2z} \rho(z)dz$$

According to the equation above, the mean backscattering intensity (I_{RB}) can be deduced by using double integrations instead of summations:

$$I_{RB}(t) = \int_0^L \int_0^L \begin{bmatrix} \left(M(z_1)\vec{E}_s(t - 2z_1/v_{gr})\right)^c \\ \bullet (M(z_2)\vec{E}_s(t - 2z_2/v_{gr})) \bullet \rho^*(z_1)\rho(z_2) \\ e^{-\alpha(z_1+z_2)} e^{j2\beta(z_1-z_2)} d_{z_1} d_{z_2} \end{bmatrix}$$

$\rho(z)$ is different at each different location and its expected value can be calculated by assuming that $\rho(z)$ meets the delta-correlated zero-mean circular-complex-Gaussian (ccG) random variable, where the expected value of $\rho(z)$ is given by:

$$\left(\rho^*(z_1)\rho(z_2)\right) = 2\sigma^2\delta(z_1 - z_2)$$

So, the final value of mean backscattered intensity is given by [16]:

$$[I_{RB}] = \frac{2\sigma^2 I_s(1-e^{-2\alpha L})}{2\alpha} = \frac{S\alpha_s}{2\alpha}(1-e^{-2\alpha L}) \bullet I_s$$

$$RB = \frac{S\alpha_s}{2\alpha}(1-e^{-2\alpha L}) \text{ \& } B = \frac{S\alpha_s}{2\alpha}; l = e^{-2\alpha L}$$

where α is the fiber attenuation, I_s is the source intensity, σ^2 is the variance of $\rho(z)$, α_s is the attenuation coefficient due to Rayleigh scattering, and *S* is the recapture fiber ratio (the fraction of the total Rayleigh-scattered power that gets captured in the fiber and propagates in the backward direction), and I_b/I_s is equal to the intensity RB coefficient. For the long span fibers (L > 20 Km), the RB coefficient rapidly converges to be $[S\alpha_s / 2\alpha]$.

3.2. Discrete Fresnel Reflections

Discrete Fresnel reflection is any local change of its geometry or its electrical characteristics that can break the symmetry of translation in the guiding structure. The sources of these discrete reflections in optical fiber link systems are basically from the refractive-index discontinuities such as in macro- or micro-bendings, fusion mechanical splices, bad or dirty connectors, filters, air-glass interfaces in connectors, and transition of guiding structure with different refractive index. The effect of discrete reflections (or multiple reflections) in transmission link got much attention and had became popular since 1980's [9], [10]. A. F. Judy have analyzed, calculated, and measured their effects in long-distance optical transmission by combining discrete Fresnel reflections and Rayleigh backscattering noise for 100 km length of fiber at 1.31 μm single-mode optical fiber [11].

Since they reduce the signal to noise ratio (SNR), these effects cause two types of power penalties in receiver sensitivities. First, multiple reflection points produce the interferometric cavity that feeds power back into the laser cavity, thereby converting the phase noise into the intensity noise. Second, multiple optical paths cause the appearance of spurious signal arriving at the receiver with variable delays, thereby causing intersymbol interference (ISI). ISI is a form of distortion of a signal in which one symbol interferes with subsequent symbols. This is an unwanted phenomenon as the previous symbols have similar effect as noise, thus making the communication less reliable which is usually caused by multipath propagation or the inherent non-linear frequency response of a channel causing successive symbols to 'blur' together. Unfortunately, these effects are signal-dependent, so that increasing the transmitted or received optical power does not improve the bit-error-rate (BER) performance. Thus, it needs to be eliminated to avoid the worse system degradations.

3.3 Analysis for Conventional WDM-PON

In theoretical analysis, Fresnel reflections in the feeder and drop fiber were labeled as r_f and r_d, respectively. Because r_f and r_d values are sufficiently small (r_f and r_d <<< 1), therefore someone can treat the reflected light as a slight perturbation to the incoming signal in which the effect of multiple reflections can be ignored. Due to the existence of Fresnel reflections noise in the fiber caused by discontinuities, certain amount of the propagating light will also be guided in backward direction (backreflected lights) and causing instructive interference with RB noise. So, the total intensity noise that received at the fiber input is given by the sum of RB and FR contributions along the optical path [12]:

$$R_{1f} = B(1-l_f^2) + r_f l_{fr}^2 \qquad R_{2f} = B(1-l_f^2) + r_f l_f^2 l_{fr}^{-2}$$
$$R_{1d} = B(1-l_d^2) + r_d l_d^2 l_{dr}^{-2} \qquad R_{2d} = B(1-l_d^2) + r_d l_{dr}^2$$

First, the analysis started with conventional WDM-PON which takes place usually for 20 km transmission distance. Loss or gain between optical line terminal (OLT) and optical network unit (ONU) is called the remote node (RN) loss or gain, respectively. The reflection points along the optical fiber are denoted by l_{fr} (feeder) and l_{dr} (drop), respectively. The distributed Rayleigh backscattering in transmission fiber is labeled by RB. The effect of OBI (optical beat interferometric) noise depends on the relative state of polarization (SOP) between the signal and the backreflected lights. The worst case occurs when the signal is co-polarized (the same polarization, Pol. = 1) with the backreflected lights. However, for the real case we can use Pol.= 0.5, this is an appropriate value since RB noise is randomly polarized light (partially polarized in nature) with its color power spectral density (PSD) proportional to the PSD of the input signal to the optical fiber). Figure 2 below shows our schematic modeling for RB and FR effects over conventional (regard RN as a loss) and long-reach (consider RN as a gain) WDM-PON.

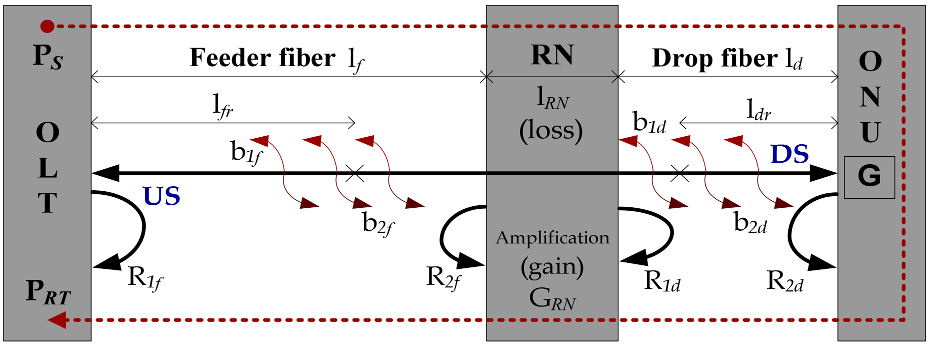

Figure 2. Schematic modeling of Rayleigh Backscattering (RB) and Fresnel Reflections (FR) over conventional (RN as a loss) and long-reach WDM-PONs (RN as a gain).

The total crosstalk power is defined as $P_C = P_{Cd\ (downstream)} + P_{Cu\ (upstream)}$

$$P_{Cd} = P_S (R_{1f} + R_{1d} l_f^2 l_{RN}^2)$$
$$P_{Cu} = P_{RONU} (R_{2f} l_{RN}^2 l_d^2 + R_{2d}) G_{RONU} l_t \qquad l_t = l_f l_{RN} l_d$$

Then the total crosstalk power is equal to:

$$P_C = P_S (R_{1f} + R_{1d} l_f^2 l_{RN}^2 + P_{RONU} (R_{2f} l_{RN}^2 l_d^2 + R_{2d}) G_{RONU} l_t$$

Usually, for the conventional WDM-PON, there is no amplification supported at the remote node (RN) area. So, the crosstalk intensity will typically be dominated only by the terms which are associated with R_{1f} and R_{2d}. It means that the terms R_{2f} and R_{1d} will be negligible, so the crosstalk just dominated by the ONU's gain value. The total crosstalk power can be simplified:

$$P_C\ (total) = P_S R_{1f} + P_{RONU} R_{2d} G_{RONU} l_t \qquad ;\ P_{RONU} = P_S G_{RONU} l_t$$
$$= P_S R_{1f} + P_S R_{2d} G_{RONU}^2 l_t^2$$
$$= P_S [R_{1f} + R_{2d} G_{RONU}^2 l_t^2]$$

If RSOA is one of the better choices for colorless reflective ONU (cost-effective reflective modulator) which is good to be used for bidirectional transmission, then the total crosstalk-to-signal ratio (C/S) for conventional WDM-PONs can be calculated as:

$$\left(\frac{C}{S}\right)=\frac{R_{1f}+R_{2d}G_{RONU}^{2}l_t^{2}}{G_{RONU}l_t^{2}}=\frac{R_{1f}}{G_{RONU}l_t^{2}}+R_{2d}G_{RONU}\rightarrow\left(\frac{C}{S}\right)=\frac{R_{1f}}{G_{RSOA}l_t^{2}}+R_{2d}G_{RSOA}$$

The above equation indicates that the crosstalk-to-signal ratio (C/S) strongly depends on the reflective ONU gain. So, to minimize the C/S value, we then find the optimal (minimal) reflective ONU gain as a function of MUX or DEMUX position. It can be obtained by taking the partial derivatives of C/S according to gain, ∂(C/S)/∂G_{RONU} = 0, resulting in:

$$G_{RONU}=\frac{1}{l_t}\sqrt{\frac{R_{1f}}{R_{2d}}}\rightarrow G_{RSOA}=\frac{1}{l_t}\sqrt{\frac{R_{1f}}{R_{2d}}}$$

Then, by plugging the result above to the C/S formula, we can get the minimal value of C/S, given by:

$$\left(\frac{C}{S}\right)_{\min,\,conventional}=\frac{2}{l_t}\sqrt{R_{1f}R_{2d}}$$

Both reflective ONU gain and crosstalk will depend on the RN loss. Besides, because R_{1f} and R_{2d} contain RB and FR, so optimal reflective ONU gain will depend on RB and the Fresnel reflections magnitude and locations along the optical fiber.

3.4 Analysis for Long-Reach WDM-PON

Now, the same model or design is applied to the long-reach WDM-PON systems. In long-reach WDM-PONs, the amplification factor is an indispensable solution, both for terrestrial and undersea lightwave communication systems. Usually, long reach takes place for 100 km or beyond transmission (by combining the metro and access networks) and for undersea optical fiber system, in-line optical amplifier is necessary placed after usually 50-80 km transmission distance to boost the signal power budget.

In [13], [14], MUX or DEMUX, such as AWG is placed at the arbitrary position along the optical link to determine the best crosstalk-to-signal ratio. Here, the key concept is that by placing the optical amplifier such as EDFA in RN area, either at the intermediate position or close to the OLT or ONU side, this system will be able to obtain the optical gain and corresponding with ONU gain also which will amplify the whole transmission link.

3.4.1 Downstream Scenario Analysis [RB-DS]:

1) Rayleigh Scattering which is produced at the output of optical line terminal (OLT) or between optical line terminal (OLT) and remote node (RN) = $RB_{OLT\text{-}RN}$

   Power of $RB_{OLT\text{-}RN}$ = $P_{OLT\text{-}RN}$ = P_S.B [1-exp (-2αL)] = P_S.B (1- l_f^2) = $P_S.R_f$
   l_n = exp (-αLn) and R_f = B (1- l_f^2)

2) Rayleigh Backscattering which is produced at the output of remote node (RN) or between remote node (RN) and reflective ONU (RONU) = $RB_{RN\text{-}RONU}$

   Power of $RB_{RN\text{-}RONU}$ = $P_{RN\text{-}RONU}$ = P_S.B (1- l_d^2) . [G^2_{RN} . l_f^2] ; R_d = B (1- l_d^2)

3.3.2 Upstream Scenario Analysis [RB-US]:

3) Rayleigh Backscattering which is produced at the output of reflective ONU or between reflective ONU (RONU) and remote node (RN) = $RB_{RONU\text{-}RN}$

   Power of $RB_{RONU\text{-}RN}$ = $P_{RONU\text{-}RN}$ = $Po\text{-}_{RONU}$. B (1- l_d^2) . [G_{RONU}. l_f . l_d . G_{RN}];

4) Rayleigh Backscattering which is produced at the output of remote node (RN) or between remote node (RN) and optical line terminal (OLT) = RB_{RN-OLT}

Power of $RB_{RN-OLT} = P_{RN-OLT} = Po_{-RONU} \cdot B\,(1- l^2_f) \cdot G^2_{RN} \cdot l^2_d$

$Po_{-RONU} = P_S \cdot [G_{RONU} \cdot l_f \cdot l_d \cdot G_{RN}]$

Crosstalk-to-signal ratio (C/S) ratio for the total crosstalk power can thus be given by:

$$\left[\frac{C}{S}\right] = B\frac{(1-l_f^2)+(1-l_d^2)G_{RN}^2 l_f^2 + (l_f l_d G_{RN} G_{RONU})^2 (1-l_d^2) + (1-l_f^2) G_{RN}^2 l_d^2 (l_f l_d G_{RN} G_{RONU})^2}{(l_f l_d G_{RN})^2 G_{RONU}}$$

$$\left[\frac{C}{S}\right] = \frac{R_f + R_d G_{RN}^2 l_f^2 + R_d (l_f l_d G_{RN} G_{RONU})^2 + R_f G_{RN}^2 l_d^2 (l_f l_d G_{RN} G_{RONU})^2}{(l_f l_d G_{RN})^2 G_{RONU}}$$

$$\left[\frac{C}{S}\right] = \frac{R_f}{l_f^2 l_d^2 G_{RN}^2 G_{RONU}} + \frac{R_d l_d^{-2}}{G_{RN}} + R_d G_{RONU} + R_f l_d^2 G_{RN}^2 G_{RONU}$$

If we use EDFA as in-line amplifier in remote node (RN) and RSOA as reflective ONU, then $G_{RN} = G_{EDFA}$ and $G_{RONU} = G_{RSOA}$. So, the crosstalk-to-signal ratio will be:

$$\left[\frac{C}{S}\right] = \frac{R_{1f}}{l_f^2 l_d^2 G_{EDFA}^2 G_{RSOA}} + \frac{R_{1d} l_d^{-2}}{G_{RSOA}} + R_{2d} G_{RSOA} + R_{2f} l_d^2 G_{EDFA}^2 G_{RSOA}$$

The first two terms are regarding to the crosstalk level of RB-DS in downstream scenario analysis and the second two terms are regarding to the crosstalk level of RB-US in upstream scenario analysis. If someone going to find the optimal RSOA gain, by taking the first derivative of C/S ratio to ONU gain (∂(C/S)/∂G_{RSOA}) equal to zero, then optimal gain can be obtained as:

$$G_{RSOA,opt} = \sqrt{\frac{R_{1f} + R_{1d} G_{EDFA}^2 l_f^2}{R_{2f} G_{EDFA}^2 l_d^2 + R_{2d}}}\left(\frac{1}{l_f G_{EDFA} l_d}\right)$$

The term inside the square root contains the roundtrip gain compensated loss ($R_{1d} G_{EDFA}^2 l_f^2 / R_{2f} G_{EDFA}^2 l_d^2$) incorporated with RB and FR between CO and ONU when employing the in-line optical amplifiers in RN area along the optical fiber transmission. This is actually matched with the work that was done by Gimlet et al. [15]. They have suggested that despite its distributed nature behavior, RB in optical fiber preceding and following an amplification node can be modeled as “Rayleigh mirrors” which might have similar effects as two discrete reflections with effective reflectance that proportional to the ratios of total backscattered power to the incident or injected power. Both these effects are potential impairments for the reliable operations and future upgrading of high speed multigigabit-per-second direct detection or coherent communication systems using commercial presently installed fiber cables. It can be said that ONU gain is also the function of RN gain compensated loss by choosing the constant distance of the reflection point locations. So, the second term is just like the inverse of RN gain compensated losses along the fiber link. Beside ONU gain, this system also has the RN gain from EDFA that was placed along the transmission link and the optimal RN gain at the fix ONU gain also can be found by taking the first derivative of C/S ratio to RN gain: ($\frac{\partial(C/S)}{\partial G_{RN}} = 0$), then it will obtain:

$$G_{RN,opt} = \frac{1}{l_d}\sqrt{\frac{1}{G_{ONU}\,l_f}} \rightarrow G_{EDFA,opt} = \frac{1}{l_d}\sqrt{\frac{1}{G_{RSOA}\,l_f}}\ .$$

4. Conclusion

Bidirectional single-fiber single-wavelength WDM PON transmission is more preferred than the unidirectional transmission due to its capacity doubling and lower cost because only half of the amount of fibers is used. However, this topology suffers from the RB crosstalk with the original light signal and additional penalties associated with discrete Fresnel reflections (FR) of connector facets or fiber splices. Although discrete reflections of connectors or splices can be suppressed, there is always an intrinsic RB loss which cannot be avoided, the portion of the isotropic directivity pattern of Rayleigh scattering that is captured by the fiber and sent back toward the source transmitter that actually limits the gain of in-line amplifier at RN and the optimal reflective ONU gain in the user vicinity. Rigorous theoretical analysis of bidirectional transmission for conventional and long-reach WDM-PON by considering the combined effects of RB and FR that induced the power penalty of receiver sensitivity has been also explained in such detail. In conventional WDM-PON, both reflective ONU gain and RB crosstalk power will depend on the RN loss value. Also, because R_{1f} and R_{2d} contain RB and FR, so optimal reflective ONU gain will depend on the RB and FR magnitude and its locations along the optical fiber. However, for long-reach WDM-PON, reflective ONU gain is obtained as the function of RN gain compensated loss by choosing the constant distance of the reflection point locations.

Refferences

[1] Keiser G, Optical Fiber Communications, Fourth Edition, McGraw-Hill, 2010: Ch. 1.

[2] Marki C F, Design and optimization of bidirectional and optical logic systems in the presence of noise. PhD Dissertation. University of California. San Diego: 2007.

[3] Gysel P, Staubli R K. Statistical Properties of Rayleigh Backscattering in Single-Mode Fibers. *J. Lightwave Technology.* 1990; 8(4): 561-567.

[4] Staubli R K, Gysel P, Hofstetter R U. Power Penalties Due to Multiple Rayleigh Backscattering in Coherent Transmission Systems Using In-Line Optical Amplifiers. *IEEE Photonics Technology Letters*. 1990; 2(12): 872-874.

[5] Gysel P, Staubli R K. Spectral Properties of Rayleigh Backscattered Light from Single-Mode Fibers Caused by a Modulated Probe Signal. *J. Lightwave Technology*. 1990; 8(12): 1792-1798.

[6] Staubli R K, Gysel P. Crosstalk Penalties Due to Coherent Rayleigh Noise in Bidirectional Optical Communication Systems. *J. Lightwave Technology.* 1991; 9(3): 375-380.

[7] Hong W. Y, Qiang N. G, Pan G, and Kun G. *Theoretical Analysis on Coherent Noise by Rayleigh Backscattering in Bidirectional Transmission System with Single Mode Fiber.* IEEE Computer Society, International Forum on Information Technology and Applications. 2009:209-212.

[8] Wang W. S, Kwon H. C, Han S. K. Suppression of Rayleigh Backscattering in a Bidirectional WDM Optical Link using Clipped Direct Modulation. *IEE Proceedings of Optoelectronics*. 2004; 151(4): 219-222.

[9] Gimlett J. L, Iqbal M. Z, Curtis L, Cheung N. K, Righetti A, Fontana F, Grasso G. Impact of Multiple Reflection Noise In Gbit/s Lightwave Systems with Optical Fibre Amplifiers. *Electronics Letters.* 1989; 25(20): 1393-1394.

[10] Gimlett J. L, Cheung N. K. Effects of Phase-to-Intensity Noise Conversion by Multiple Reflections on Gigabit-per-Second DFB Laser Transmission Systems. *J. Lightwave Technology.* 1989; 7(6): 888-895.

[11] Judy A. F. *Generation of interference intensity noise from fiber Rayleigh backscatter and discrete reflections*. Proceeding of OSA/OFC'91. San Diego, California. Paper WL-4: 110.

[12] Lin S. C, Lee S. L, Lin H. H, Keiser G, and Ram R. J. Cross-Seeding Schemes for WDM-Based Next-Generation Optical Access Networks. *J. Lightwave Technology*. 2011; 29(24): 3727-3736.

[13] Lopez E. T, Lazaro J. A, Arellano C, Polo V, Prat J. Optimization of Rayleigh-Limited WDM-PONs With Reflective ONU by MUX Positioning and Optimal ONU Gain. IEEE Photonic Technology Letters. 2010; 22 (2): 97-99.

[14] Lopez E. T, Lazaro J. A, Arellano C, Polo V, Prat J. *ONU Optimal Gain and Position of the Distribution Element in Rayleigh-limited WDM and TDM PONs with reflective ONU.* Proceeding of ECOC 2009, Vienna, Austria. Paper P6.27.

[15] Gimlet J. L, Iqbal M. Z, Cheung N. K, Righetti A, Fontana F, Grasso G. Observation of Equivalent Rayleigh Scattering Mirrors in Lightwave Systems with Optical Amplifiers. *IEEE Photonics Technology Letters*. 1990; 2(3): 211-213.