VOL. 12, NO. 17, SEPTEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

CHARACTERISTIC OF WAVELENGTH DIVISION MULTIPLEXING PASSIVE OPTICAL NETWORK

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ABSTRACT

This paper is the first to demonstrate and simulated a simple and systematic transfer matrix (T-matrix) method for analyzing the accumulated effects of Rayleigh Backscattering (RB) and Fresnal reflection (FR) crosstalk on signal transmission in bidirectional single-fiber WDM-PON systems for the conventional (usually 20 km transmission without any amplification in remote node) and comparing with the analytical methods. Secondly by using analytical method we are going to analyse the three cases for long-reach WDM-PONs (100km by utilizing optical amplifier to enhance the power budget) in the first case the best crosstalk-to-signal (C/S) is achieved when the Remote Node (RN) is placed either near to the Central office (CO) or Optical Network Unit (ONU) section. And in the second case, we are going to achieve the best effective crosstalk-to-signal (C/S) ratio when the Remote Node (RN) gain is placed at the middle of transmission link. And in the third case, the crosstalk-to-signal (C/S) ratio gets worse nearly by 1.5 dB in the presence of a strong reflection (r = 30 dB). Eventually if the FR is increased by the smaller reflectivity and therefore EDFA gain must be exaggerated, the crosstalk-to-signal (C/S) ratio will even get worse when EDFA is placed near to ONU section. This happens due to the reamplification and re-modulation feedbacks of back reflections that may occur in the Transmission of the signal at Remote Node (RN). This transfer matrix method is efficient, powerful (when comparing with the analytical methods). Its accuracy is verified for straight forward system architectures and then applied for complex architectures of long-reach hybrid WDM-PONs.

Keywords: bidirectional transmission, cross-seeding scheme, fresnel multiple reflections, rayleigh backscattering, transfer matrix method, WDM-PON system.

INTRODUCTION

There is an increase in the demands for large number of users for data bandwidth but the fact that it is relatively expensive in many cases to introduce the new fiber installation, indicates that better ways in which should be found to extend the capability on existing design, While at identical time conjointly cut back the operational expenses (opex). The most agreeable ways that to extend the capacity is by a way known as wavelength division multiplexing passive optical network (WDM-PON) and colorless optical network unit (ONU) is most preferred to cut back the operational expenses (opex). Rayleigh backscattering (RB) and Fresnal reflection (FR) will be major impairments within the technology that utilizes the wavelength division multiplexing passive optical network (WDM-PON) loop-back technique [1-5] as shown in Figure-1. The loop-back technique is usually applied in WDM-PONs to avoid the employment of colored upstream transmitters. Seeding lights are transmitted from the optical line terminal (OLT) at the central office (CO) to the optical network units (ONUs), wherever upstream signals are encoded on the seeding lights with modulation devices, like injection-locked Fabry-Perot (IL-FP) lasers, reflective semiconductor optical amplifiers (RSOAs), reflective electro-absorption modulators (REAMs), and integrated REAM with the semiconductor optical electronic equipment (REAM-SOA) [6-8]. Once a single-fiber is employed to transmit the seeding light and also the upstream signal, Rayleigh backscattering (RB) and Fresnal reflection (FR) will cause optical beat interferometric (OBI) noise. The extent of FR in such optical systems will be alleviated by selecting optical parts with acceptable loss and punctiliously handling fiber conjunction and association. RB, the other major intrinsic impairment in fiber propagation and its level is set by the fiber sort and configuration used. In these systems, RB will cause severe degradations to upstream transmission once signals are transmitted on the full-duplex fiber configuration. The effects of RB and FR on WDM-PON systems are intensively investigated mistreatment analytical strategies [9-11]. However, the prevailing approaches might encounter some difficulties once handling complicated system structures. Such complicated cases embrace the long-reach hybrid WDM on prime of your time division multiplexing (TDM) PON structures, wherever a mix of optical gain and optical power splitters or demultiplexers is used at the remote node (RN), and multiple stages of optical gain area unit required within the systems. To our information, this paper is that the 1st to demonstrate a straight forward and systematic transfer matrix (T-matrix) technique for analyzing the accumulated effects of RB and FR on signal transmission in numerous sort of signal fiber bidirectional WDM-PON systems.

The rest of this paper is organized as follows. Section one and two describes T-matrix analysis for systems with back-reflections. Section three verifies that for basic WDM-PON systems with loop-back schemes, the entire, crosstalk-to-signal (C/S) ratio that springs with the transfer matrix will cause similar results that are often rumored with in the literature. In Section four we simulated the plot results for an easy design wherever the analytical answer will be derived and investigate the

accuracy of the T-matrix technique. Section five provides the detail performance analysis by action the variations because of the usage of AWG and EDFA in standard and long-reach model, severally. The T-matrix technique is then applied to research additional difficult hybrid WDM/TDM PON systems. Section six and seven shows some simulation results for long-reach WDM-PONs with and without FR effects that is by considering the RB effect only, and the other is by combining the RB plus FR effects together using analytical methods to describe the effective position of EDFA. Lastly, Section eight provides some conclusions.

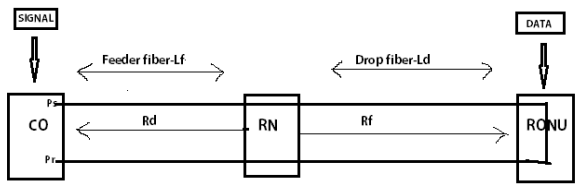

Figure-1. Mechanism of a loop-back of basic WDM-PON system with Rayleigh backscattering (RB) and Fresnel reflection (FR) for single-fiber transmission.

Analysis of T-matrix method for systems with back-reflections

T-matrices **are** applied to model the transmission and reflection characteristics of optical devices and systems. Referring to Figure-2, the transfer matrix of a two-port block is outlined as:

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix} \text{.....}(1)$$

Here, Ai and Bi represent the forward-going and backward-going powers at the i-th port, where i=1 and a pair of severally. T-matrix for the entire structure is just the matrix product of the individual matrices for all of the sections.

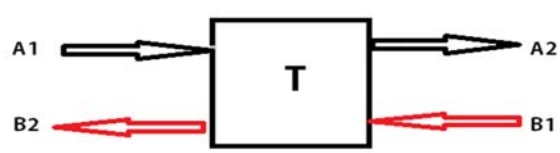

Figure-2. Typical model of one transfer matrix with input and output powers.

The Rayleigh backscattering originating from distributed reflection on the fiber is typically treated as incoherent interference. And the Fresnel reflection effect would possibly interfere with the signal coherently, on the relative path distinction between the reflections and signals. The ability of T-matrix deals with solely those interferences out of coherent length from the received signal. This assumption is often adopted to deal with the reflections in fiber transmission systems, as well as WDM-PON systems [12].

In Figure-3, Ps is the initial seeding power sent from the source at CO; PBR-UL is that the total disturbance power that comes from the effects of both RB and FR on the loop-back upstream transmission. Pr is the received power of the transmission signal. Pf, Prn, Pd, and PONU are the T-matrices for the feeder fiber, remote node, drop fiber, and optical network unit. P_u is the t-matrix of the upstream transmission. Every T-matrix shown in Figure-3 will represent a series of passive or active elements, and P_u may be obtained by multiplying the matrices of all building blocks for the transmission.

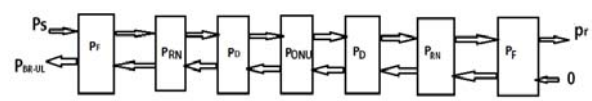

Figure-3. T-matrix model for the upstream scenario of a WDM-PON system with the loop-back scheme.

PBR-UL accounts for each the back-reflections of the downstream injected seeding light-weight at CO (Type I) and also the modulated upstream signal at ONU (Type II) .When the signal passes through the second ONU and may be dominant once the ONU provides high gain to the upstream transmission. The input/output relation of the full system are often expressed by:

$$\begin{bmatrix} P_s \\ P_{BR-UL} \end{bmatrix} = P_u \begin{bmatrix} P_R \\ 0 \end{bmatrix} = \begin{bmatrix} P_{u11} & P_{u12} \\ P_{u21} & P_{u22} \end{bmatrix} \begin{bmatrix} P_R \\ 0 \end{bmatrix} \text{.....}(2)$$

The received signal power, is obtained by not considering the RB and FR effects in Eq. (2) as:

$$\begin{bmatrix} P_s \\ 0 \end{bmatrix} = P^*_u \begin{bmatrix} P_{R0} \\ 0 \end{bmatrix} = \begin{bmatrix} P^*_{u11} & P^*_{u12} \\ P^*_{u21} & P^*_{u22} \end{bmatrix} \begin{bmatrix} P_{R0} \\ 0 \end{bmatrix} \text{.....}(2a)$$

Where P^*_u is that the total transfer matrix calculated by not considering the RB and FR effect. The C/S ratio for the upstream transmission is outlined because the ratio of the power, PBR-UL, to the received signal power. From Eqs. (2) and (2a), the C/S ratio is given by:

$$\left(\frac{C}{S}\right)_u = \frac{P_{BR-UL}}{P_{R0}} = P^*_{u11}\left(\frac{P_{u21}}{P_{u11}}\right) \quad (3)$$

Similarly, modelling for the downstream transmission will be written as:

$$\begin{bmatrix} P_T \\ P_{BR1} \end{bmatrix} = P_{dn} \begin{bmatrix} P_{Rdn} \\ 0 \end{bmatrix} = \begin{bmatrix} P_{dn11} & P_{dn12} \\ P_{dn21} & P_{dn22} \end{bmatrix} \begin{bmatrix} P_{Rdn} \\ 0 \end{bmatrix} \quad (4)$$

Where P_T, P_{Rdn}, and P_{BR1} signify the transmitted downstream power, received downstream power, and back-reflected power. The T-matrix for the downstream transmission, P_{dn}, includes the unidirectional building blocks from the CO transmitter to the ONU receiver. The interference contribution are often obtained by subtracting the received signal power while not considering the impairments, PRdn0, from PRdn. Therefore, the C/S quantitative relation for the downstream transmission is given by:

$$\left(\frac{C}{S}\right)_d = \left(\frac{P_{Rdn} - P_{Rdn}0}{P_{Rdn}0}\right) = \left(\frac{P^*_{dn11}}{P_{dn11}} - 1\right) \quad (5)$$

Where the superscript "*" refers to the matrix component for the downstream transmission without considering the RB and FR effects.

Typically, major impairments caused by the RB and FR effects in single-fiber loop-back type WDM-PONs occur in or by the upstream transmission. Thus, following discussions and calculations can concentrate on the transmission direction.

Fresnel reflection equation

The separation is modelled by the reflection (R) and transmission (Γ) power coefficients as

$$T_{FR} = \frac{1}{\tau}\begin{bmatrix} 1 & -R \\ R & \tau^2 - R^2 \end{bmatrix} \quad (6)$$
$$\tau = 1 - R$$

Feeder or drop fiber Coefficients

The loss of a feeder or drop fiber will be written as lf, ld; αf, αd being the fiber loss coefficients, Lf, Ld be the lengths. The subscripts f and d denote the feeder fiber and therefore the drop fiber. The relative RB power will be written as, wherever B = Sαs/2α is that the RB constant, with S being the fiber recapture constant (dimensionless) and αs [km–1] is the fiber scattering coefficient

$$l_f = \exp(-\alpha_f L_f)$$
$$l_d = \exp(-\alpha_d L_d)$$
$$g_f = B(1 - l_f^2)$$
$$g_d = B(1 - l_d^2)$$
$$B = \frac{S\alpha_s}{2\alpha}$$

C/S ratio of basic WDM-PON systems with loop-back scheme

In this section, we are going to show that, for basic WDM-PON systems, the C/S ratio derived by the transfer matrix technique ends up in results that similar to those obtained with analytical approaches. With the transfer matrix technique, the relationships among the seeding power, received power, FR, and RB given by Eq. (1). Power Transfer matrix is the results of matrix operation, i.e., Pu=Pg*Ph, wherever Pg is that the overall transmission matrix from CO to ONU, and Ph is that the overall transmission matrix from the ONU back to the CO. Under these conditions, Pg is written as:

$$P_g = \frac{1}{l_f}\begin{bmatrix} 1 & -g_f \\ g_f & l_f^2 \end{bmatrix}\frac{1}{l_{RN}}\begin{bmatrix} 1 & 0 \\ 0 & l_{RN}^2 \end{bmatrix}\frac{1}{l_d}\begin{bmatrix} 1 & -g_d \\ g_d & l_d^2 \end{bmatrix}\frac{1}{G_{onu}}\begin{bmatrix} 1 & 0 \\ 0 & G_{onu}^2 \end{bmatrix} \quad (7)$$

We can compose this as:

$$P_g = \frac{1}{G_{onu} l_f l_{rn} l_d}\begin{bmatrix} P_A & P_B \\ P_C & P_D \end{bmatrix} \quad (8)$$

Where

$$\begin{aligned} P_A &= 1 - l_{RN}^2 g_f g_d \\ P_B &= G_{onu}^2\left[-l_{RN}^2 g_f l_d^2 - g_d\right] \\ P_C &= g_f + l_{RN}^2 g_d l_f^2 \\ P_D &= G_{onu}^2\left[l_{RN}^2 l_f^2 l_d^2 - g_d g_f\right] \end{aligned} \quad (9)$$

Similarly,

$$P_h = \frac{1}{l_f}\begin{bmatrix} 1 & -g_d \\ g_d & l_d^2 \end{bmatrix}\frac{1}{l_{RN}}\begin{bmatrix} 1 & 0 \\ 0 & l_{RN}^2 \end{bmatrix}\frac{1}{l_f}\begin{bmatrix} 1 & -g_f \\ g_f & l_f^2 \end{bmatrix} = \frac{1}{l_f l_{rn} l_d}\begin{bmatrix} P_P & P_Q \\ P_R & P_S \end{bmatrix} \quad (10)$$

Where

$$\begin{aligned} P_P &= 1 - l_{rn}^2 g_f g_d \approx 1 \\ P_Q &= -l_{rn}^2 l_d^2 g_f - g_f \\ P_R &= g_d + l_{rn}^2 l_d^2 g_f \\ P_S &= l_{rn}^2 l_d^2 l_f^2 \end{aligned} \quad (11)$$

From Eqs. (9) and (11)

$$P_{u11} \approx M\left[1 - G_{ONU}^2 (g_d + g_f l_{RN}^2 l_d^2)^2\right] \quad (12)$$

The second approximation in relative Equation (12) applies once the cyclic term is much smaller than one. The approximation is usually smart as a result of γf (γd) is sometimes less than -30 dB and GONU < 20 dB. Under such conditions and from Equation (3), P*u11≈Pu11 .Thus, C/S quantitative relation may be obtained as: Thus, C/S ratio can be obtained as:

$$\left(\frac{c}{s}\right)_u \approx P_{u21} = M\ (P_c P_p + P_d P_r) \quad (13)$$

the C/S ratio is expressed by:

$$\left(\frac{c}{s}\right)_u = \frac{g_f}{G_{onu} l_f^2 l_{rn}^2 l_d^2} + \frac{g_d}{G_{onu} l_d^2} + G_{onu} g_f l_{rn}^2 l_d^2 + G_{onu} g_d \quad (14)$$

This result's the same as that obtained with the approximate analytical methodology for the essential WDM-PON system. In Section four, this finding is valid by our calculated results.

CALCULATED RESULTS AND DISCUSSIONS

In order to verify the accuracy achieved in the T-matrix then results are going to be compared with those calculated in the analytical formula. Then, these techniques are going to be applied to investigate the long-reach hybrid PON systems wherever the analytical formula is troublesome to derive. In the calculations S, αs, α at λ=1550nm are given in the table. The C/S ratio is calculated with MATLAB programs.

Table-1. Simulation parameters.

Design parameters	**Value** (unit)
Fraction ratio, S	0.0015
Fiber attenuation (α)	4.6 x 10^{-5}/m (0.2 dB/Km)
Feeder Fiber and Drop Fiber Length (L_f & L_d)	20, 50, 100 Km
Fresnel Reflection *r* → *return loss*	30 dB (strongest reflection) (range: 30-70 dB)
RN Gain, G_{RN}	10, 15 dB
Insertion Loss, l_{RN}	5 dB
RONU Gain, G_{RONU}	10-20 (dB)

Case 1. WDM-PON systems with Fresnel reflections

To validate the accuracy of study achieved victimisation T-matrix, we tend to calculate the straightforward system structure of a single-fiber loop-back WDM-PON network wherever the reflections and multiple Rayleigh back scatterings are completely analyzed with the analytical formula [5]. In this network, the OLT and ONU square measure connected with a fiber within which a separation with Fresnel reflection happens. To match our notations, the separation is assumed to be the remote node, and also the two fiber sections divided by the separation correspond to the feeder fiber and drop fiber (see the inset in Figure-7). For comparison, the analytical equation of the C/S magnitude relation for all interferences touching the upstream signal is rewritten as

$$\left(\frac{C}{S}\right)_u = \frac{g_t}{G_{onu} l_t^2} + \frac{R}{G_{onu} l_d^2} + \frac{(1-R)R[g_d + G_{onu}]}{1 - R l_d^2 G_{onu}} + \frac{g_t G_{onu}}{1 - g_t G_{onu}} + g_f R \quad (15)$$

Where *l'* and *gt* stand for the loss and RB effect of the whole fiber, respectively,

$$l' = l_d l_f$$

Analytical method equation (1):

$$\left(\frac{C}{S}\right) = B\frac{(1-l_f^2) + (1-l_d^2)A^2 l_f^2 + (l_f l_d A)^2 (1-l_d^2) g^2}{(l_f l_d A)^2 g} \quad (16)$$

Figure-4 compares the results obtained using t-matrix method and compares with the analytical method in the below plots.

The simulation is for two different reflection losses and three different ODN losses (l'). In the computing process, the reflection is assumed to occur at the ONU side, i.e., ld = 1; in addition, the RB effect is neglected. The two methods generate the same results for the low-reflection case (R = 60 dB), revealing a small discrepancy at the higher-gain regime for the R = 30 dB case. Both methods predict the steep increase in the C/S ratio as the gain approaches the return loss value.

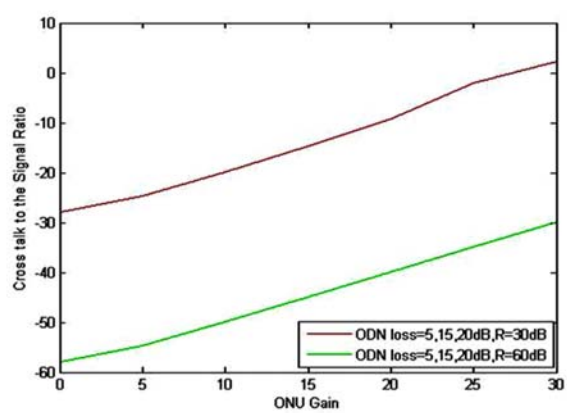

Figure-4(a). Cross talk to the signal ratio(c/s) vs ONU gain (T-matrix method).

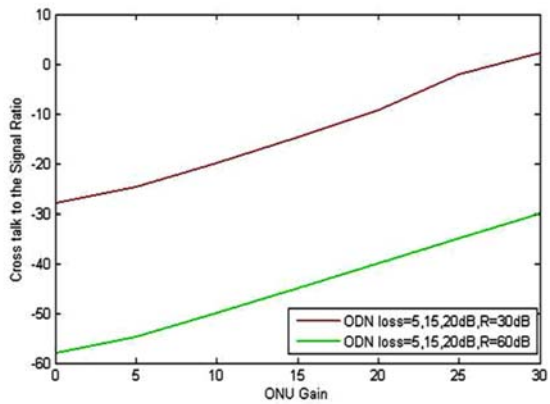

Figure-4(b). Cross talk to the signal ratio(C/S) vs ONU gain (Analytical method)

Figure-4(a) shows the C/S ratio as a function of ONU gain when B=0; for various values of losses in T-matrix method, Figure-4(b) shows the C/S ratio as a function of ONU gain for when B=0; for various values of losses in analytical method.

In the Figure-5, the calculated C/S ratios for various values of link loss and reflections when B ≠ 0. Again, the two strategies provide an equivalent results except at the acute cases wherever the C/S ratio rises steeply. The calculated C/S is concerning an equivalent for up to 25 dB of ONU gain. With Analytical model, the C/S curves reach infinity once G = 30 dB and R = 30 dB, as can be seen from relative Equations (16). With T-Matrix model, the infinite C/S quantitative relation happens once GONU = 28.7dB. For similar derivation of Equations (7) to (12) during this specific case (ld=1). In Equation (15), the cyclic effects of RB and FR effects are treated singly whereas they are combined in T-matrix modeling. If the two effects are combined, the T-matrix predicts the system performance easily and there can be an earlier breakdown once the ONU gain increases. In spite of the discrepancy at the extraordinarily high-gain regime, the two strategies provide the same results for typical operation conditions.

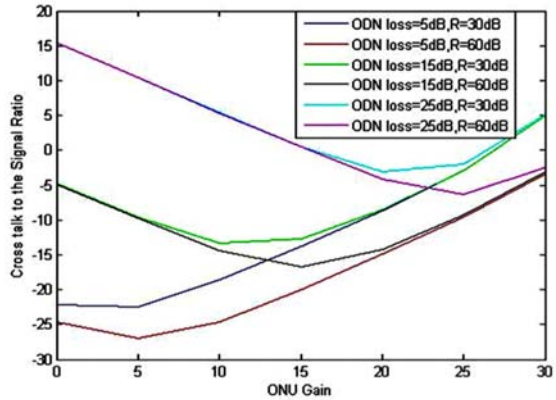

Figure-5(a). Cross talk to the signal ratio(C/S) vs ONU gain (T-matrix method).

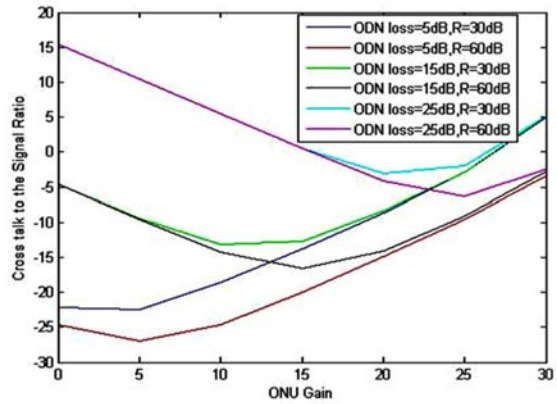

Figure-5(b). Cross talk to the signal ratio(C/S) vs ONU gain (Analytical method).

Figure-5(a) shows the C/S ratio as a function of ONU gain for various values of link loss and reflections when B ≠ 0 for T-matrix method, Figure-5(b) shows the C/S ratio as a function of ONU gain for various values of link loss and reflections when B ≠ 0 , for analytical method.

The calculated C/S versus the location of RN for various ONU gains is shown in Figure-6(a). The results are calculated only by considering the RB effect. The simulations show that the approximations considering in the T-matrix method and analytical method Equation (16) shows the same C/S ratios.

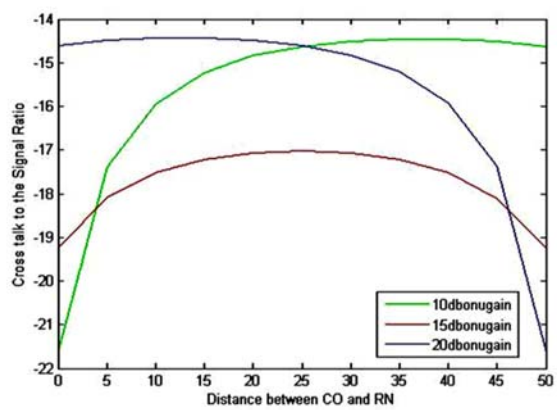

Figure-6(a). Cross talk to the signal ratio(C/S) vs Distance between CO and RN (T-matrix method).

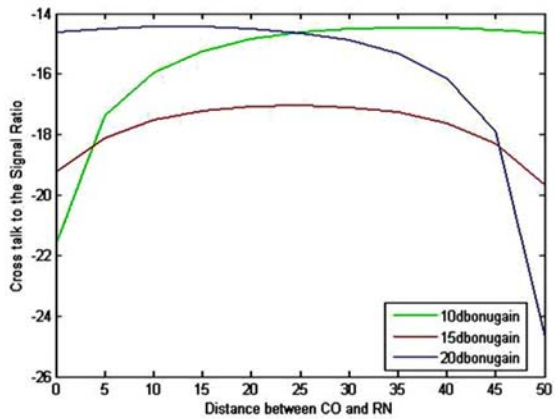

Figure-6(b). Cross talk to the signal ratio(C/S) vs Distance between CO and RN (Analytical method).

Figure-6(a) shows the calculated upstream C/S ratio to the distance between CO and RN position for a basic WDM-PON system with RN loss equal to 5 dB at different back losses and various ONU gain values. The entire fiber length (Lf + Ld) is 50 kilometer when considering only RB effect and comparing with the analytical method in Figure-6(b)

We additionally apply the T-matrix to calculate the performance of a basic WDM-PON system when FR happens and compare the results with those effective reflection approximations [13]. The new C/S ratio can be obtained by replacing the RB terms in Equations with the effective reflections. With in the calculation, we have a tendency to assume that the FR is found at each edges of the RN.

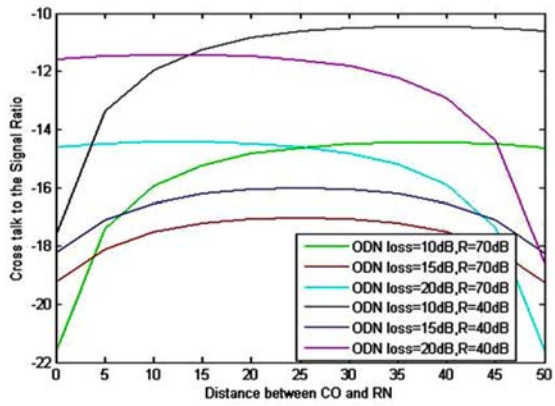

Figure-7(a). Cross talk to the signal ratio(C/S) vs Distance between CO and RN (T-matrix method).

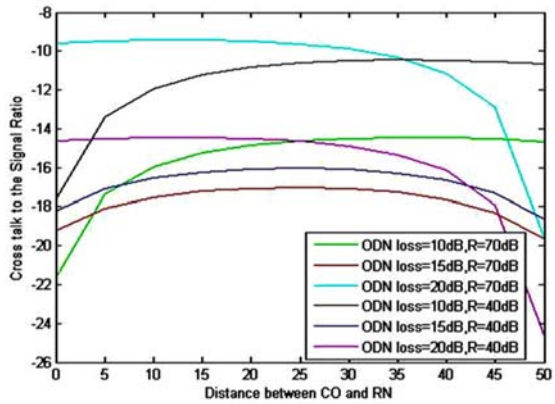

Figure-7(b). Cross talk to the signal ratio(C/S) vs Distance between CO and RN (Analytical method).

Figure-7(a) shows the calculated upstream C/S ratio to the distance between CO and RN position for a basic WDM-PON system with RN loss equal to 5 dB at different back losses and various ONU gain values. The entire fiber length (Lf + Ld) is 50 kilometer when considering both RB and FR effects and then comparing with the analytical method in Figure-7(b)

Case 2. Long-reach hybrid WDM/TDM PON systems

After performing and verifying the T-matrix method, we are going to investigate the consequences of RB on long-reach hybrid PON systems. These systems cover the span of 100KM or beyond and supports for hundreds to thousands of users. Optical amplifiers are required with in the intermediate stages to minimize the fiber propagation loss. Figure 8 shows a long-reach hybrid WDM/TDM PON system. The cases involved in this is one uses a reflective modulator whereas the opposite uses a tunable optical device as an upstream transmitter at the ONU. In each cases, only RB effects are considered.

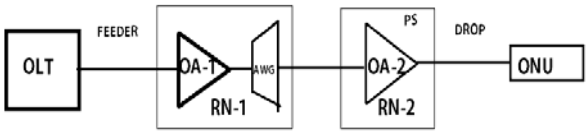

Figure-8. Long-reach hybrid WDM/TDM-PON system that can serve thousands of users.

The system consists of two-way EDFAs, connected by circulators at either side [14, 15]. At the ONU side a reflective modulator is employed to modulate and re-amplify the information for upstream transmission for loop-back design. The second optical electronic (OA-2) equipment primarily compensates for the loss at RN-2. Rayleigh backscattering will have a lot of severe impact on the system performance of a long-reach PON than on a basic one attributable to the three fiber sections and multiple gain stages concerned. The optimal C/S

quantitative relation depends on the lengths of the feeder and drop fibers yet as the optical gain of every node.

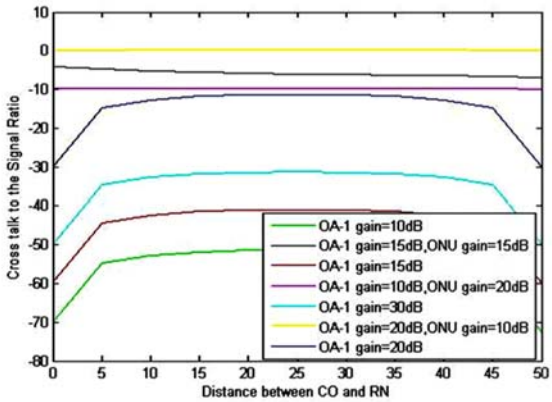

Figure-9. Cross talk to the signal ratio(C/S) vs Distance between CO and RN.

Figure-8 also shows the calculated C/S ratio as a function of the RN-1 location for the same hybrid WDM/TDM PON system however considering the different cases as using tunable lasers as upstream transmitters and reflective modulator. The upstream C/S ratio calculation shows that the RB contribution on the upstream signal happens owing to the double Rayleigh backscattering effects (RB which is twice amplified by the OA-1 gain). The calculated results indicate a negligible effect of RB except at the condition of 30 dB OA-1 gain.

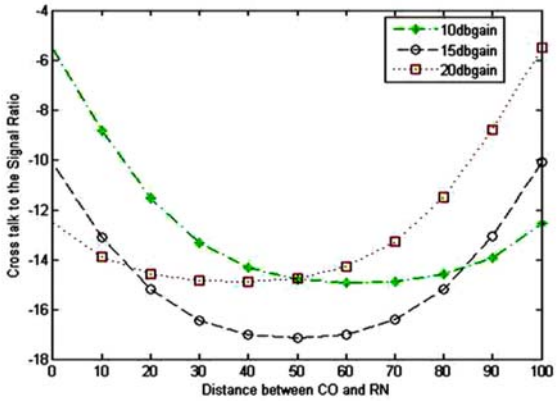

Figure-10. Cross talk to the signal ratio(C/S) vs Distance between CO and RN.

In the figure, C/S ratio plotted as a function of 100 Km fiber length for ONU gain varies from 10-20 dB with 5 dB EDFA gain by considering only RB effect. The lowest C/S ratio is obtained in the middle of distance between CO and RN. The results are plotted by using the analytical methods.

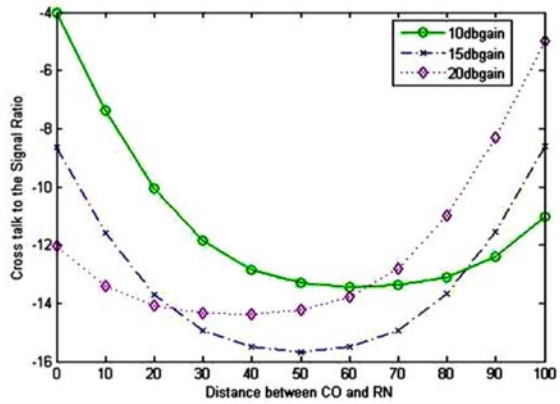

Figure-11. Cross talk to the signal ratio(C/S) vs Distance between CO and RN.

In the figure, C/S ratio plotted as a function of 100 Km fiber length for ONU gain varies from 10-20 dB with 5 dB EDFA gain by considering only RB effect. The lowest C/S ratio is obtained in the middle of distance between CO and RN.

The results are plotted by using the analytical methods

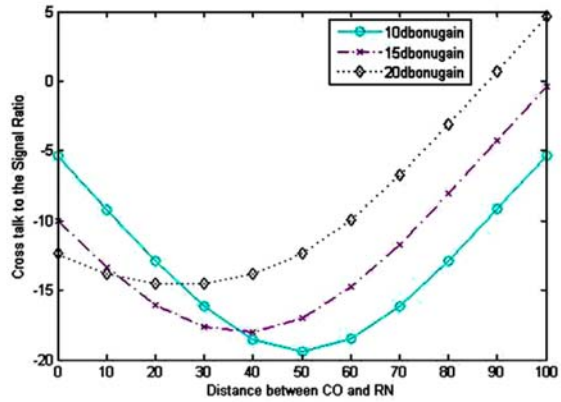

Figure-12. Cross talk to the signal ratio(C/S) vs Distance between CO and RN.

C/S ratio as a function of 100 Km fiber length for ONU gain varies from 10-20 dB with 10 dB EDFA gain w/ minimum FR loss = 60 dB.

CONCLUSIONS

We have demonstrated the simulations for WDM-PON systems using T-matrix method. The C/S ratio of the whole system can be calculated by the matrix elements of the simple loop back link and the results were compared with the existing analytical approach. The compared results are equivalent with the analytical approach except in extreme cases, and the reason for this discrepancy has been known. So by this results shows that approximations of the method strategies will employ the correct results. Additionally, T-matrix method has been applied to

corroborate the system performance of bidirectional long-reach hybrid WDM/TDM-PONs, wherever additional stages of optical gains and more fiber sections are concerned. T-matrix modeling is a methodology for analyzing the optical transmission with many sections and combinations of multiple reflections and back scatterings. EDFA is best placed at the middle of transmission link to reinforce the ability budget and to prevent the result of fiber nonlinearities which will happen in high power injection level for long-reach WDM-PON that is deployed for a 100 kilometer or beyond. By combining RB and FR effects, it was incontestable that the C/S ratio gets worse by nearly 1.5 dB within the presence of a powerful reflection. If the FR is maintained at a similar reflectivity, the C/S ratio can increase once the EDFA gain is accrued and it is due to a re-amplification and re-modulation feedback of reflections that happening at the preceding and following of the RN gain. Within the future we have a tendency to apply this method for mitigating the Rayleigh interference noise within the complex architectures of long-reach hybrid PONs.

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