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Backscattering Interferences in WDM Optical Transmission System

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Abstract

Wavelength division multiplexed-passive optical networks (WDM-PONs) are attractive solutions for future broad band access networks. However, WDM can be relatively expensive to implement owing to the cost of the specified wavelength sources. The reflective structure is a common solution to solve this problem. There is a Reflective Semiconductor Optical Amplifier (RSOA) at the Optical Network Unit (ONU) in reflective structure. Bidirectional transmission over a single fiber is applied in WDM transmission system, as it uses a single source at the Center Office side and reduces the requirement number of the fiber and cost, but also injects the Rayleigh backscatterings. A RSOA and the other reflective components in Optical Distribute Network (ODN) generate reflection. These two interferences are critical noise on the single fiber transmission system. In this paper, we have studied the influences of the reflections and Rayleigh backscattering interferences by theoretically analysis and experiment.

Keywords: *WDM, RSOA, Backscattering Interference, Crosstalk to Signal Ratio, PON*

1. Introduction

Wavelength Division Multiplexed Passive Optical Networks (WDM PON) are a promising approach for future Gigabit optical access architectures. The advantages of WDM PON are as following: (i) they allow infrastructure sharing and just-in-time provisioning of fiber drops/terminal equipment; (ii) they eliminate the need for time-multiplexing and ranging protocols; (iii) they provide virtual point-to-point connections with data transparency and a high degree on data security and independence [1]. A reflective structure at the WDM-PON transmission system is employed more and more popular.

In this paper, we talk about the influence on the passive optical networks transmission with reflective structure ONU and give theoretically analyzed and experimentally. Generally two wavelengths are needed per user to separate up- and downstream signals. Frequency Shift Keying or Phase Shift Keying on downstream data and re-modulating in on-off Keying have been investigated to re-use the downstream signal as upstream signal, signal erasing with a saturated semiconductor optical amplifier (SOA), re-modulation with a Reflective SOA(RSOA). The reflective structure at the ONU consists of a reflective RSOA, a loop comprising an optical amplifier and an external modulator, or a self-injected FP laser [2]. In seeded-light WDM-PONs, carrier signals for the ONUs (usually CW light) are generated at the central office (CO) and injected towards the ONUs. There, the carrier is modulated with

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the corresponding upstream data and sent back to the optical line termination (OLT) at the CO.

In optical full-duplex transmission, there are three main signals in the fiber: the downstream data and the carrier, in downlink direction; the upstream data in upstream direction. In upstream direction, data signals will create the Rayleigh backscattering and back-reflections from the passive components along the optical distribution network (ODN), which is yielded by the reflection semiconductor optical amplifier (RSOA). The upstream signal suffers twice the fiber attenuation and other component issues, so we will get very low of the upstream signals. It is important to consider the interferences of the upstream signals. In large ODNs that supply a high number of users, amplification may be required. Within an ODN, the amplification is performed at the remote nodes, by means of doped fiber, and at the ONUs by employing reflective semiconductor devices [3].

The ONU gain would be chosen limited in the bidirectional transmission. As show in [4], by selected an optical value for the gain at the ONU, we should consider the link losses. The amplifier increases not only the upstream signals, but also the power of the reflective and backscattering light. In the recommendation ITU-T G.984 to the bidirectional transmission scheme, the ONU gain should cover the ODN losses, which might be up to 30 dB for a Class C network. Because of the reflected and backscattering point, high levels are needed. So the ONU gain becomes a critical parameter when designing the PONs.

2. Upstream Impairments in Single Fiber Transmission System

In a WDM-PON with a RSOA transmission system, there are two signals in the upstream direction, the carrier signal (downstream) and the modulated data (upstream). However, there are additional signals inside the fiber consequents of the RB effect and due to potential reflections from passive components along the ODN. And also, one group of signals derives directly from the carrier and data upstream. Figure 1 illustrates all of the impairments; the indexes denote whether interference has Rayleigh nature ("RB"), or stem from a discrete reflection point ("RE"). As following, list all the interferences.

(I) $Carrier_{RB}$: backscattering of the carrier signal;

(II) $Carrier_{RE}$: reflection of the carrier signal;

(III) $Carrier_{RB\_RE}$: reflection of the backscattering signal in the upstream direction;

(IV) $Data_{RB}$: backscattering of the upstream data signal;

(V) $Data_{RE}$: reflection of the upstream data signal;

(VI): $Data_{RB\_RE}$ reflection of the backscattering signal in the downstream direction.

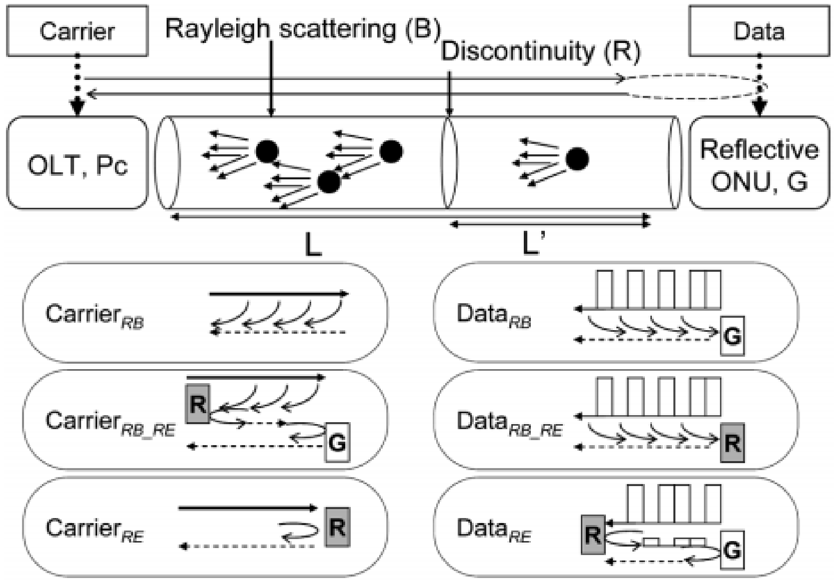

Figure. 1 The module of link transmission system and the interference signals of the upstream direction

The first interference $Carrier_{RB}$ is the backscattering of the carrier signal in the downstream direction. It is generated due to the Rayleigh scattering in the optical fibers. So $Carrier_{RB}$ is always existed in the transmission system, for a long link, for instance, longer than 20km, with a large attenuation, the value of the $Carrier_{RB}$ is constant about -34dB, depending the fiber coefficient [5].

Reflections interference happened if there is a discontinuity in the link of transmission system. As illustrated in the Figure 1, $Carrier_{RE}$ and $Carrier_{RB\_RE}$ are generated separately due to the carrier signal and the backscattering of the carrier signal.

In the second group, generated by the upstream data signal, the most harmful interference is the backscattering of data ($Data_{RB}$), because it is amplified by the received amplifier in the ONU. $Data_{RE}$ is the reflection of the upstream data and it is also a critical impairment as the reflective point near the ONU. $Data_{RB\_RE}$ is the reflection of the backscattering of the upstream data, it is not important due to the low value in the system.

The definition and the analytic description for the upstream interference signals listed above are given as following. However, in the downstream direction, we can get all the definition and the analytic description using the same expression. In this paper, we just analysis the upstream interference signals neglected the downstream direction.

2.1. Rayleigh backscattering of the carrier

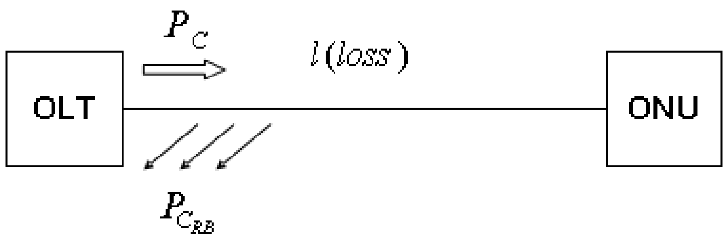

Figure. 2 The model for explanation the mechanism of the creation of $P_{C_{RB}}$

When the transmission light is injected in the optical fiber, the Rayleigh backscattering is generated in opposite direction, as shown in Figure 2. From literature, if we know the B, the length of light transmission and the injected power, we can get the power of the Rayleigh backscattering, the formula is given as:

$$P_{C_{RB}} = P_C B(1 - \exp(-2\alpha L)) \tag{1}$$

Where P_C is the transmission power in the OLT, and $B = s\alpha_s/(2\alpha)$, with α_s [km^{-1}] the fiber scattering coefficient which of the value is a little smaller than α, s the fiber recapture coefficient (dimensionless), and α [km^{-1}] the attenuation coefficient with the generation value 0.2 in 1550nm fiber. L is the length of the fiber in transmission link. Where we denote $\exp(-\alpha l)$ as l. So formula (1) is also written as following:

$$P_{C_{RB}} = P_C B(1 - l^2) \tag{2}$$

$P_{C_{RB}}$ is constant when L is large, for instance, more than 20 km. Because the scattering coefficient is constant with a fixed fiber, and $1-\exp(2\alpha L)$ is more or less equaled to 1 when L is big enough. As talk about above, $P_{C_{RB}}$ is about -34dB generally when the Pc is 0dB.

2.2. Reflection of the carrier

The reflective components in the optical transmission system occur single reflections. There are two particular conditions: Near End Crosstalk (NEXT) and Far End Crosstalk (FEXT) refer to a reflection point located at the OLT or at the ONU, respectively [6]. Because of the splices and distribution elements in transmission link, reflections occur.

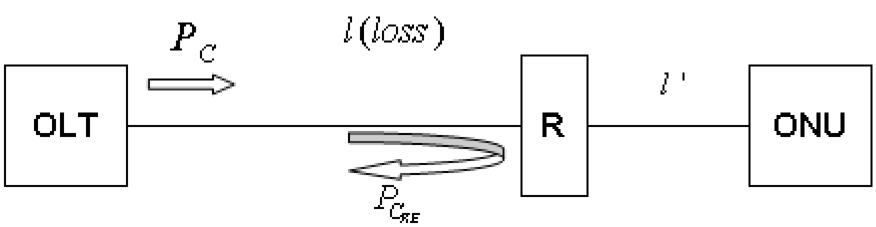

Figure. 3 The model for explanation the mechanism of the creation of $P_{C_{RE}}$

From the Figure 3, it is easy to get the expression of $P_{C_{RE}}$, the link loss between OLT and the reflection point is $\exp(-2\alpha(L-L'))$, multiplying the corresponding return loss. The mathematical expression of signal Carrier $_{RE}$ is given by:

$$P_{C_{RE}} = P_C \exp(-2\alpha(L-L'))R \tag{3}$$

Where L' is the distance from the reflective point to the ONU and R is the corresponding return loss with the value 10-60dB generally. We denote $\exp(-\alpha L')$ as l', so formula (3) can be written as:

$$P_{C_{RE}} = P_C R(l/l')^2 \tag{4}$$

In NEXT condition, transmission and receiver connect with a coupler directly. So $P_{C_{RE}}$ is a critical interference in this condition, especially for data signals with poor extinction ratio as it happens in direct modulated SOAs. However, regarding typical OLT configurations, the up- and down-link paths are merged by means of an optical circulator and therefore a possible reflection are strongly attenuated [7]. On the contrary, the FEXT condition is not important in the case of a link loss with high loss due to the twice attenuation of the reflection.

2.3. Reflection of the RB of the carrier

In a reflective structure transmission system, there is a reflective amplifier in the ONU. The signal transmitted by fiber is amplified, modulated and redirected to OLT. The reflective signal in the direction of the ONU may cause a backscattering due to RSOA, the Carrier $_{RB\_RE}$ is occurred in the uplink direction. This circle is never ending and depending on the distance and the value of the return loss, leads to a – re-modulation feedback.

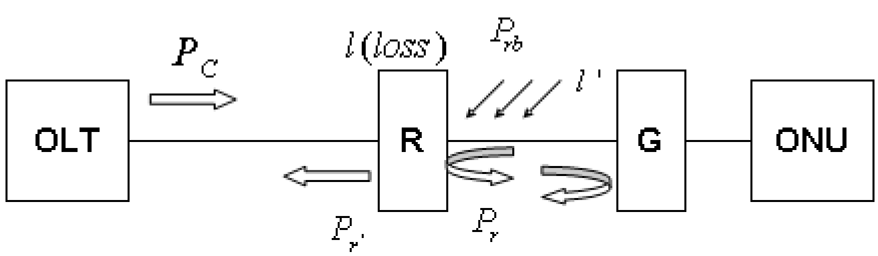

Figure. 4 the model for explanation the mechanism of the creation of $P_{C_{RB\_RE}}$

P_C injects into the optical fiber, from the analysis of the formula (1), we know that, the Rayleigh backscattering between reflection point and the amplifier is:

$$P_{rb} = P_c B(l/l')(1-l'^2) \tag{5}$$

Where l/l' is the link loss between OLT and reflection point.

Due to the RSOA, the Rayleigh backscattering is re-amplified and re-modulated and there are infinite terms of interferences. The loss between reflection point and the amplifier can be given as:

$$\sum_{n=1}^{\infty}(Rgl^{'2})^n \tag{6}$$

We note the power in the reflective point with the same direction as P_r. The other direction, the power in that point is $P_{r'}$. $P_{r'}$ retransmit to OLT, then the power of the reflection of the backscattering is got.

$$P_r = P_c B(l/l^{'})(1-l^{'2})R\sum_{n=1}^{\infty}(Rgl^{'2})^n \tag{7}$$

It is to get $P_{r'}$ as following:

$$P_{r'} = P_c B(l/l')(1-l'^2)(\sum_{n=1}^{\infty}(Rgl'^2)^n)(1-R) \tag{8}$$

After l/l' link loss, the expression of Carrier RB_RE is given as following:

$$\begin{aligned} P_{C_{RB\_RE}} &= P_C B(l/l^{'})^2(1-R)(1-l^{'2})\sum_{n=1}^{\infty}(Rl^{'2}g)^n \\ &= P_C B(l/l^{'})^2(1-R)(1-l^{'2})Rl^{'2}g/(1-Rl^{'2}g) \\ &= P_C Bl^2(1-R)(1-l^{'2})Rg/(1-Rl^{'2}g) \end{aligned} \tag{9}$$

Where, g is gain of the ONU. For simplification, the exponential terms have been substituted by $l=\exp(-\alpha L)$ (the entire loss in one direction) and $l^{'}=\exp(-\alpha L^{'})$ (the loss between the reflection point and the ONU).

2.4. Rayleigh Backscattering of the upstream data

The second group of the interferences is generated by the modulated data signal in upstream direction. The carrier transmits through by the optical fiber, received by the ONU, amplified, modulated with data signal and retransmit to OLT.

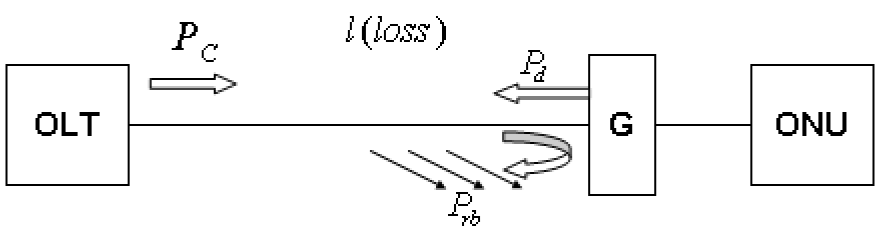

Figure. 5 the model for explanation the mechanism of the creation of $P_{D_{RB}}$

In Figure 5, the transmission power of ONU is P_d, the expression of P_d is as following:

$$P_d = P_c gl \tag{10}$$

The backscattering of P_d is:

$$P_{rb} = P_d B(1-l^2) \tag{11}$$

Then the backscattering of P_d transmit to the OLT with l link loss and g amplifying, the expression of the Data $_{RB}$ is given by the following:

$$P_{D_{RB}} = P_C B(1-l^2) l^2 g^2 \tag{12}$$

But we get this formula without considered the subsequent backscattering and upstream amplified terms. The two interferences will create RB again, and the process continues infinite. With take into account both noise, the expression will develop into:

$$\begin{aligned} P_{D_{RB}} &= P_C l^2 \sum_{n=1}^{\infty} B^n (1-l^2)^n g^{n+1} \\ &= P_C l^2 B(1-l^2) g^2 / (1 - B(1-l^2) g^2) \end{aligned} \tag{13}$$

In this formula, we will find that the interference Data $_{RB}$ increasing with the squared gain, when increase the signal by amplifier, Data $_{RB}$ is also amplified. Data $_{RB}$ may lead to systems limitations.

2.5. Reflection of the upstream data

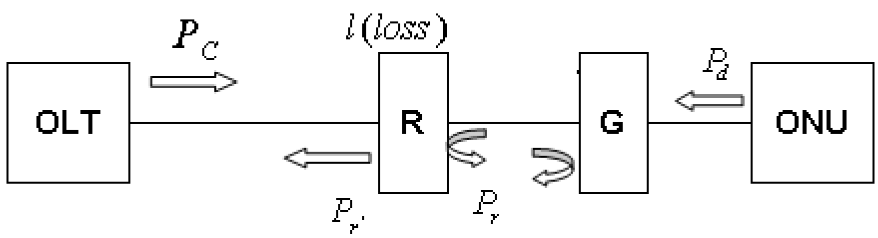

Figure. 6 The model for explanation the mechanism of the creation of $P_{D_{RE}}$

The reflection of the upstream data is a critical noise in the reflective transmission system, as it also depends on the squared gain. Data $_{RB}$ will comprise of the consequence of a reflection in the direction of the ONU, the same situation as Carrier $_{RE}$. It can also lead to a re-alimented loop which is still worse in this situation due to the signal that reflects has larger power [8]. The expression of $P_{r'}$ is:

$$P_r^{'} = P_c g l (1-R) (\sum_{n=1}^{\infty} (R g l^{'2})^n) l^{'} \tag{14}$$

Then the expression of Data $_{RB}$ is give as following:

$$\begin{aligned} P_{D_{RE}} &= P_C l^2 (1-R) g \sum_{n=1}^{\infty} (Rl^{'2} g)^n \\ &= P_C l^2 (1-R) g R l^{'2} g / (1 - Rl^{'2} g) \\ &= P_C (ll^{'})^2 (1-R) g^2 R / (1 - Rl^{'2} g) \end{aligned} \tag{15}$$

From the formula (15), we can find that the reflection of data is critical as the same as the backscattering of the data since they all depend on the squared gain. In general, the backscattering coefficient (B) is more or less 35dB, in a worse NEXT condition, the $l^{'}$ is equal to 1, a normal return loss of the passive devices (R) is 35dB. In this condition, from the expression (14) and (15), we will get the same value of them.

2.5. Reflection of the RB of the data (Data $_{RB\_RE}$)

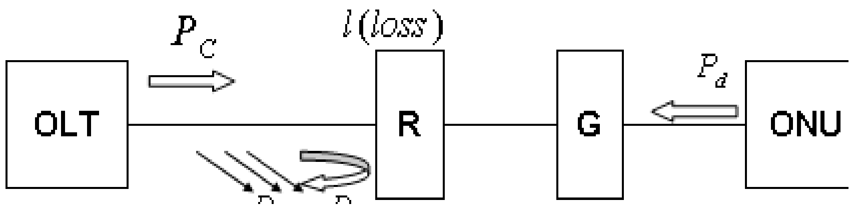

Figure. 7 The model for explanation the mechanism of the creation of $P_{D_{RB\_RE}}$

By the same mechanism that creates Carrier $_{RE}$, the backscattering of the data signal might also be reflected to the OLT. But it is different because it depends directly on the gain of the ONU.

The backscattering between OLT and R is:

$$P_{rb} = P_d l B (1 - (l / l^{'})^2) \tag{16}$$

Then the backscattering is reflected by the RSOA, and the expression is given by:

$$P_{D_{RB\_RE}} = P_C B l^2 (1 - (l / l^{'})^2) R g \tag{17}$$

3. Crosstalk to Signal Ratio Analysis and Experiment Confirmation

3.1. Crosstalk to signal ratio

Here, we have simulated the crosstalk to signal ratio for each interferences, the power of the signal in the upstream direction is:

$$P_s = P_c g l^2 \tag{18}$$

So C/S for each interferences is given by following:

$$C / S_{C_{RB}} = B(1 - l^2) / (l^2 g) \tag{19}$$

$$C/S_{C_{RE}} = R/(l^{'2}g) \tag{20}$$

$$C/S_{C_{RBRE}} = B(1-R)(1-l^{'2})R/(1-Rl^{'2}g) \tag{21}$$

$$C/S_{D_{RB}} = Bg(1-l^{2})/(1-Bg(1-l^{2})) \tag{22}$$

$$C/S_{D_{RE}} = l^{'2}R(1-R)/(1-Rl^{'2}g) \tag{23}$$

$$C/S_{D_{RBRE}} = BR(1-(l/l^{'})^{2}) \tag{24}$$

The total sum of all the interferences affecting the upstream transmission, leads to an optical crosstalk to signal ratio in the upstream direction expressed as following:

$$\begin{aligned} C/S = \sum P_i/(P_C l^2 g) = (B/g)(l^{-2}-1) + R/(gl^{'2}) + \\ R(1-R)((1-l^{'2})B + gl^{'2})/(1-Rl^{'2}g) + \\ B(1-l^2)g/(1-B(1-l^2)g) + B(1-(l/l^{'})^2)R \end{aligned} \tag{25}$$

The parameters of the network are listed as following:

i. The coefficient of Rayleigh backscattering B;

ii. The ONU gain g;

iii. The total link loss l;

iv. The loss between reflection point and the ONU $l^{'}$;

v. The return loss of passive devices R;

In a communication system, an optimal gain is important performance [9]. Here we talk about how much the gain is optimal. In optimal gain, we can get the smallest Crosstalk to Signal Ration. The most important interferences in upstream direction are backscattering of carrier and upstream data, so the problem reduces to the interferences Carrier ^{RB} and Data ^{RB}.

$$\begin{aligned} C/S = (P_{C_{RB}} + P_{D_{RB}})/P_S = (P_C B(1-l^2) + P_C B(1-l^2)l^2g^2)/P_C l^2 g = \\ B/l^2g + Bg - B/g - Bl^2 g \end{aligned} \tag{26}$$

We set $\partial(C/S)/\partial g = 0$, it means that we will get the best performance at this point, Then we get the optimal ONU gain as following:

$$g_{opt} = 1/l \tag{27}$$

From formular (27), we will get the optimal ONU gain at point with the same value of total link loss.

3.2. Experiment confirmation

In this part, we simulate the Crosstalk to Signal Ration of all interferences.

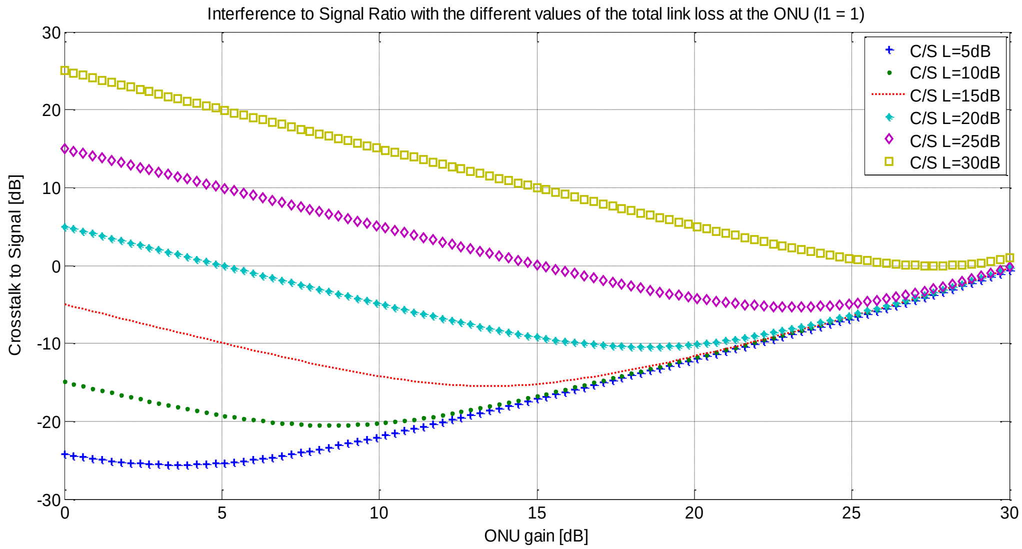

Figure 8. Total crosstalk to signal ratio with some link loss and different gain

As show in Figure 8, we simulate the total C/S with different ONU gain in some constant link loss. From formula 27, the optimal point is that the ONU gain is equal to link loss. However, the result is got in condition just considering two interferences backscattering of carrier and upstream data. In Figure 8, we consider all the interferences, so the optimal point is more or less 3dB smaller than theory analysis. So in realistic design, the optimal ONU gain is 3dB smaller than the total link loss.

4. Conclusion

In a single fiber transmission system, the backscattering of carrier and upstream data ate the most important interferences. When the ONU gain is smaller about 2-3dB than the total link loss, the total gets lowest, it is mean that the transmission system has the best performance in this condition. When design a realistic optical transmission system, it is always required large value of gain to get higher received power, however, the backscattering interferences seem to be an impediment in the optical transmission system design. Otherwise this thesis focuses on point-to-point transmission system.

In realistic WDM PON network design, there are multiplexers, splitters and filters, which can filter the noise, the restrictions of ONU gain can be relaxed due to these components. And also multiple reflections along the fiber can be suppressed by careful system design such as by using obliquely polished connectors, fusion splices, and high return loss passive components, suppression of Rayleigh backscattering-generated interferometry noise poses some fundamental limitations. In this thesis, we consider the worst case. In realistic design, we can select useful components and more effective technologies to degrade the influence of Rayleigh backscattering and reflection. When design an optical transmission system, the suggestion optimal ONU gain is 3dB below total link loss.

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