

# A Raman amplified GPON reach extension system using parameters of a deployed fiber

Lufeng Leng,<sup>\*</sup> and Think Le

Physics Department, New York City College of Technology, 300 Jay Street, Brooklyn, NY 11201, USA  
[lleng@citytech.cuny.edu](mailto:lleng@citytech.cuny.edu)

**Abstract:** Recently distributed Raman amplification of the upstream signal has been proposed to improve the loss budget for gigabit passive optical networks (GPON), and systems of 60-km reach and up to 128 way split have been demonstrated employing state-of-the-art fibers. However, a deployed fiber plant may not perform as well due to elevated fiber attenuation, splice losses, and back-reflections that are present in a realistic GPON system. In this paper, their effects on the Raman amplified 1310-nm upstream signal in a GPON reach extension system is investigated numerically. Using the parameters of a deployed fiber, a design solution is provided for a purely passive, Raman amplified GPON reach extender. Results show that 55-km logical reach and 1:32 split ratio can be achieved using a realistic fiber plant and class B + transceivers.

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## 1. Introduction

Gigabit passive optical networks (GPONs) have been recently deployed world-wide [1, 2] and are expected to play a critical role in meeting the ever increasing bandwidth demand of subscribers. Although the GPON protocol [3] supports a maximum logical reach of 60 km and up to 128 users, in practice most GPON deployments are limited to a split ratio of 32 and reach of up to 20 km due to the 28-dB loss budget of the class B + specification [4].

Recently distributed Raman amplification has been proposed to improve the loss budget and extend the reach of a GPON system. In order to maintain the outside fiber plant completely passive [5–8], a Raman pump can be placed at the central office (CO) to provide distributed gain in the feeder fiber for the upstream signal, while a high power signal source or a semiconductor optical amplifier (SOA) can be exploited for the downstream signal. Employing such scheme a GPON extension system of 60-km reach and 1:128 split ratio has been demonstrated using class C + transceivers and forward error correction (FEC) in a laboratory setup [8], where the fiber was new and no splice was present along the feeder fiber. In deployed GPON systems, however, the benefits of distributed Raman amplification may be reduced due to likely lossier fiber and splice losses, leading to lower Raman gain and optical signal-to-noise ratio (OSNR). In addition, back-reflections at the splices may cause multiple-path interference (MPI), thus further degrading the signal integrity [9, 10]. It is important to quantify the additional impairments caused by the above mentioned non-ideal conditions and evaluate the performance of a Raman amplified GPON reach extension system with realistic fiber parameters.

An analytical method has previously been derived to estimate the Raman gain and noise figure of a distributed Raman amplifier with localized losses for metro area transmission systems [11]. However, it assumes that the fiber attenuation coefficient is the same for both the signal and pump wavelengths, which results in large errors if applied to GPON systems. Moreover, it does not consider the impact of MPI caused by back-reflections at connectors or splices.

In this paper, we investigate numerically the OSNR degradations of the upstream signal caused by elevated fiber attenuation, splice losses, and back-reflections in a Raman amplified GPON reach extender. Using the parameters of a deployed GPON system, we provide a design solution capable of 60-km logical reach and 1:32 split ratio. This is achieved with class B + specification and without FEC.

## 2. Modeling

The GPON reach extension system considered in this work is shown in Fig. 1. The Raman pump for the 1310-nm upstream signal and the 1490-nm downstream signal are combined by a CWDM coupler at the CO and sent to the 50-km feeder fiber. The 1490-nm signal power is boosted by an SOA. The 1310-nm signal enters the feeder fiber after traversing a CWDM at the optical network unit (ONU), a distribution fiber of up to 10 km, and a 1:N power splitter at the remote node (RN). For simplicity, uniform lengths are assumed for the spliced segments of the feeder fiber. The evolutions of the signal, pump, noise channels, and their backscattered powers in the feeder fiber can be described by a set of coupled steady-state equations as shown in Eq. (1), which are based on the standard model of a distributed Raman amplifier [12,13]:

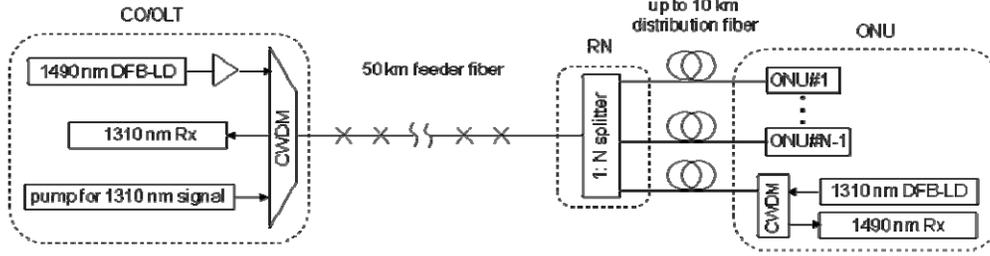


Fig. 1. A Raman amplified GPON reach extension system.

$$\begin{aligned}
 \frac{d}{dz} P^{\pm}(z, \nu_i) = & \mp \alpha(\nu_i) P^{\pm}(z, \nu_i) \pm \gamma(\nu_i) P^{\mp}(z, \nu_i) \\
 & \pm \sum_{m=1}^{i-1} C_R(\nu_m - \nu_i) [P^{\pm}(z, \nu_m) + P^{\mp}(z, \nu_m)] \left\{ P^{\pm}(z, \nu_i) + 2h\nu_i \left[ 1 + \frac{1}{e^{h(\nu_m - \nu_i)/KT} - 1} \right] \Delta\nu \right\} \\
 & \mp \sum_{m=i+1}^n \frac{\nu_i}{\nu_m} C_R(\nu_i - \nu_m) P^{\pm}(z, \nu_i) [P^{\pm}(z, \nu_m) + P^{\mp}(z, \nu_m)] \\
 & \pm \sum_{m=i+1}^n \frac{\nu_i}{\nu_m} C_R(\nu_i - \nu_m) \left[ 2h\nu_i \left( \frac{1}{e^{h(\nu_i - \nu_m)/KT} - 1} \right) \Delta\nu \right] [P^{\pm}(z, \nu_m) + P^{\mp}(z, \nu_m)] \\
 & \mp \sum_{n=1}^{L/L_{sp}} \alpha_{sp} P^{\pm}(z, \nu_i) \delta(z - nL_{sp}) \pm \sum_{n=1}^{L/L_{sp}} \alpha_r P^{\mp}(z, \nu_i) \delta(z - nL_{sp})
 \end{aligned} \quad (1)$$

In the above,  $P^+(z, \nu_i)$  and  $P^-(z, \nu_i)$  are the optical powers of the forward- and backward-propagating waves within the bandwidth  $\Delta\nu$ , respectively. The fiber loss coefficient is represented by  $\alpha$ , whereas the recaptured Rayleigh backscattering is given by the coefficient  $\gamma$ . The Raman gain efficiency is  $C_R \equiv g_R/A_{eff}$ , where  $g_R$  is the Raman gain coefficient scaled to the pump wavelength, and  $A_{eff}$  is the effective mode area. The coefficients  $h$  and  $k$  are Planck's constant and Boltzmann's constant, respectively, whereas  $T$  is the fiber temperature. Both the spontaneous emission (in the third term) and the absorption (the fifth term) are included in the model, with the factor of 2 accounting for the two polarization modes of the fiber. For stimulated emissions, the optical powers at frequencies from  $m=1$  to  $m=i-1$  amplify the signal at frequency  $\nu_i$ , whereas the optical powers at frequencies from  $m=i+1$  to  $m=n$  attenuate the signal. The frequency ratio  $\nu_i/\nu_m$  ensures photon conservation. The pumps are polarization scrambled. The last two terms correspond, respectively, to losses and back-reflections at splices, with  $\alpha_{sp}$  being the splice loss,  $\alpha_r$  the return loss,  $L_{sp}$  the length of each spliced fiber segment, and  $L$  the total length of the feeder fiber.

### 3. Results and discussion

#### 3.1 The baseline performance

We chose a commercially available state-of-the-art single-mode fiber as the reference fiber to be used in the GPON reach extension system so that the baseline performance can be understood. The fiber has a peak Raman gain efficiency of 0.39/(W·km) for a 1550-nm signal pumped by a depolarized 1450-nm laser source. After gain scaling with respect to the pump wavelength [9] it is found that the maximal Raman gain efficiency for the 1310-nm signal is 0.60/(W·km) when pumped by a depolarized 1240-nm source. The fiber attenuation is 0.42 and 0.32 dB/km at 1240 and 1310 nm, respectively. The Rayleigh backscattering coefficient is  $1.15 \times 10^{-4} \text{ km}^{-1}$  at 1310 nm.

The 1310-nm signal power was set at -23 dBm at the entrance of the feeder fiber, corresponding to 21-dB loss of a 1:64 power splitter at the RN, 4-dB loss of the distribution

fiber (up to 10 km), 1-dB loss of the CWDM coupler at the ONU, and a 3-dBm laser output power [7, 8]. Due to its low input power to the distributed fiber amplifier, the 1310-nm upstream signal is degraded by the Raman amplified spontaneous emission (ASE) noise and thus its OSNR is a critical measure of the signal quality. Depending on the amount of Raman gain or pump power, the 1310-nm signal may also suffer from double Rayleigh backscattering (DRB).

Using the parameters of the reference fiber without splices, the baseline performance of the GPON reach extender can be obtained by solving Eq. (1) numerically. In Fig. 2(a), we use  $OSNR_{ASE}$  to describe the ASE accumulation and  $OSNR_{MPI}$ , the ratio of signal power to DRB power, to characterize the amount of MPI. The  $OSNR_{ASE}$  increases with the pump power initially and reaches the maximum at a pumping level of 1150 mW due to rapid ASE accumulation at the high pump power. However, at this point the  $OSNR_{MPI}$  has dropped to 25 dB, a level of crosstalk that could lead to 1-dB power penalty [14, 15]. In this work we set the  $OSNR_{MPI}$  threshold at 35 dB in order to keep the effect of DRB at a negligible level. The optimal pump power is then determined by the  $OSNR_{MPI}$  threshold. According to Fig. 2(a), the optimal pump power is approximately 920 mW and the corresponding  $OSNR_{ASE}$  is 19.1 dB with 0.1-nm resolution bandwidth. To put the  $OSNR_{ASE}$  into perspective we note that in [7, 16] error-free transmissions were achieved with OSNRs of 18 dB/0.1 nm using class B + receivers.

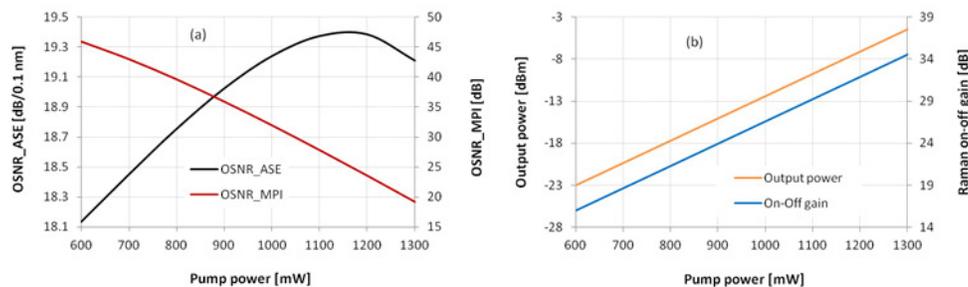


Fig. 2. (a) OSNRs of the 1310-nm signal vs. the 1240-nm pump power. (b) 1310-nm signal power at the exit of the feeder fiber and the Raman on-off gain.

The 1310-nm signal power exiting the feeder fiber and the Raman on-off gain are plotted in Fig. 2(b). Due to the low input signal power of  $-23$  dBm, no saturation in the Raman gain or the output power was observed. It is worth pointing out that across the range of the pump power in Fig. 2(b), the received power of the 1310-nm signal at the CO is above  $-28$  dBm, the receiver sensitivity requirement of a class B + system [4].

### 3.2 The performance of a realistic system

We added fiber attenuation, splice losses, and back-reflections one at a time to the reference fiber system and evaluated the corresponding performance of the 1310-nm signal. In the first step, the reference fiber attenuation was increased for both the signal and the pump by 0.01, 0.03, and 0.05 dB/km, respectively, to simulate the possible conditions of a lossier fiber link. The resulting performance of the 1310-nm signal is shown in Fig. 3. For comparison the reference fiber with 0.32-dB/km attenuation coefficient at 1310 nm is also included. As expected, both the  $OSNR_{ASE}$  (Fig. 3(a)) and Raman gain (Fig. 3(b)) decrease with the elevating fiber loss. On the other hand, the MPI power is also reduced, leading to the improved  $OSNR_{MPI}$  as shown in Fig. 3(a). This allows more pump power for the lossier fiber link. Using the 35-dB  $OSNR_{MPI}$  threshold, the optimal pump power can be determined for each case. For instance, it increases from 920 mW for the reference fiber to 1010 mW for the fiber with 0.35-dB/km attenuation coefficient at 1310 nm. It can be further seen that the achieved  $OSNR_{ASE}$  are 18.7, 17.8, and 16.9 dB/0.1 nm for the attenuation coefficients of 0.33, 0.35, and 0.37 dB/km, respectively, at 1310 nm.

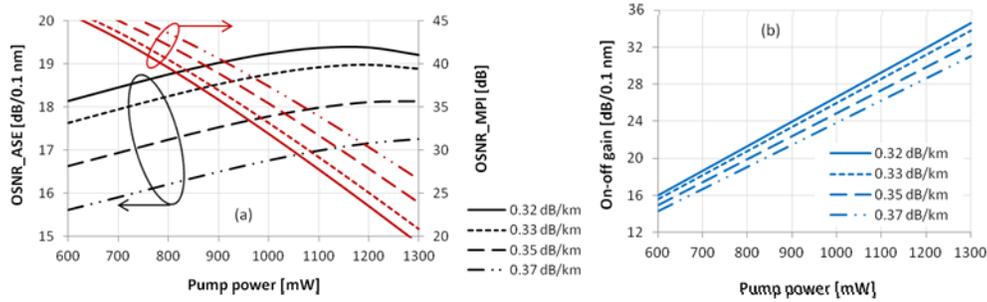


Fig. 3. (a) OSNRs of the 1310-nm signal for various attenuation coefficients. (b) Raman on-off gain for various attenuation coefficients at 1310 nm.

In the next step we chose the fiber with 0.35-dB/km attenuation coefficient at 1310 nm, and introduced splice losses along its length. We assumed that the 50-km feeder fiber consisted of segments of a uniform length, which was varied from 1 to 5 km in the calculations. For a splice loss of 0.01, 0.03, and 0.05 dB [17], respectively, at the beginning of each segment, the OSNR<sub>ASE</sub> dependence on the segment length is computed and shown in Fig. 4. The case of no splice loss is also drawn in the solid line. As before the pump power has been optimized for each case to achieve the highest OSNR<sub>ASE</sub> while keeping the MPI at 35 dB. It falls between 1000 and 1100 mW depending on the splice loss. It can be seen that the OSNR<sub>ASE</sub> is reduced rapidly as the fiber segment length shortens, or equivalently, the number of splices increases. Specifically, if the segment length is 2 km between adjacent splices, the OSNR<sub>ASE</sub> decreases by 0.2 dB for every 0.01-dB increment of the splice loss; for 0.05-dB loss at each splice the OSNR<sub>ASE</sub> drops to 16.7 dB/0.1 nm. The results suggest that it is critical to manage the splice losses and reduce the number of short fiber segments. Note that a pair of mating connectors typically introduce 0.3-dB loss [18], therefore their use should be limited in a Raman amplified GPON system.

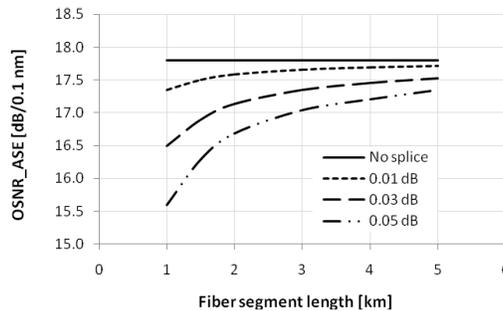


Fig. 4. OSNRs of the 1310-nm signal. The fiber attenuation coefficient is 0.35 dB/km at 1310 nm. Both the splice loss and segment length are varied.

Lastly we examined the impact of back-reflections on the 1310-nm upstream signal, for which the following parameters were employed for a realistic GPON reach extender: 0.45-dB/km attenuation at 1240 nm, 0.35-dB/km attenuation at 1310 nm, and a 0.05-dB splice loss at the beginning of each 2-km fiber segment. The return loss of a splice was varied from 30 to 50 dB. Without back-reflections the OSNR<sub>ASE</sub> is 16.7 dB/0.1 nm, as indicated by the solid line in Fig. 5. When back-reflections are taken into account the OSNR<sub>ASE</sub> is further degraded by an amount that depends on the return loss, as shown in Fig. 5. What happens here is that the back-reflections result in more MPI light, which must be suppressed by reducing the pump power so that the same OSNR<sub>MPI</sub> (35dB) is maintained. For example, the optimized pump power for the case of 40-dB return loss at each splice is reduced to 960 mW. As a result, the corresponding OSNR<sub>ASE</sub> is reduced to 16.3 dB/0.1 nm. A fusion splice typically has better than 50 dB return loss, whereas a pair of mating connectors has a return loss of 30

to 40 dB [19]. Therefore the use of connectors should be at least minimized if not prohibited in a Raman amplifier. We would like to point out that in comparison to the reference fiber system discussed in Section 3.1, the 16.3-dB/0.1 nm OSNR<sub>ASE</sub> reflects a 2.8-dB reduction, which is the sum of 1.3 dB due to the increased fiber loss, 1.1 dB due to the splice losses, and 0.4 dB due to the back-reflections. Without FEC it is not likely for such a GPON reach extension system to support 64 ONUs and 60-km logical reach (50-km feeder fiber + 10-km distribution fiber).

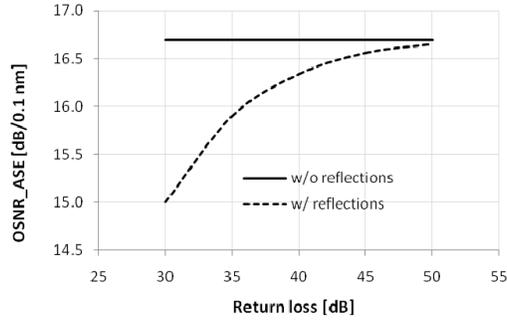


Fig. 5. OSNRs of the 1310-nm signal when splice return losses are taken into account.

### 3.3 The link loss budget of a realistic system

To determine the maximum number of ONUs that can be supported by the above mentioned GPON system with the same 50-km feeder fiber length, the 1310-nm power launched into the feeder fiber was varied from  $-23$  to  $-17$  dBm to reflect the loss budget of the 1:N splitter, the distribution fiber, and the ONU. The assumed feeder fiber parameters are: 0.35-dB/km attenuation at 1310 nm, 0.05-dB splice loss and 40-dB return loss at the beginning of each 2-km fiber segment. The dependence of the OSNR<sub>ASE</sub> on the 1310-nm input power is calculated and depicted in Fig. 6. The result shows that the input power must be more than  $-21.3$  dBm in order to achieve better than 18-dB/0.1 nm OSNR<sub>ASE</sub>. Given a minimum ONU transmitter power of 0.5 dBm, 1-dB loss of a CWDM combiner in the ONU, 2-dB loss of a 5-km distribution fiber, and 17.5-dB loss of a 1:32 splitter, the 1310-nm input power into the feeder fiber becomes  $-20$  dBm, leading to 19.3 dB/0.1 nm OSNR<sub>ASE</sub>. Thus we conclude that it is feasible for a 1:32 split GPON deployment to extend its logical reach to 55 km (50-km feeder fiber + 5-km distribution fiber) via distributed Raman amplification of the upstream signal. Although the optical filter bandwidth in front of the receiver is not required in the simulations, for system implementation, it can be set at 20 nm, which is similar to that used in [7, 8] and compliant to the ITUT standard.

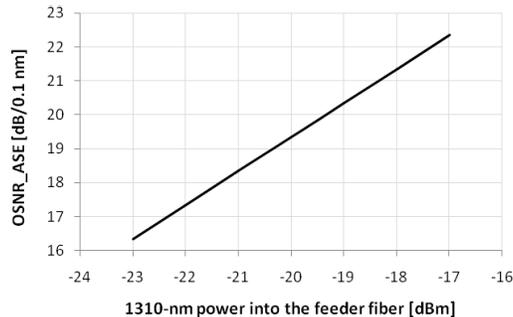


Fig. 6. OSNRs of the 1310-nm signal vs. its input power to the feeder fiber.

The link loss budget for the realistic GPON reach extender considered here is detailed in Table 1. For the 1310-nm upstream signal, the optimal pump power is 960 mW and it provides 22.6-dB on-off gain. This level of pump power presents rigorous requirement on eye safety precaution and connector and fiber management. For the 1490-nm downstream signal, the fiber attenuation coefficient is set at 0.25 dB/km. According to Table 1, a saturation power of 8 dBm is required of the SOA to meet the receiver sensitivity requirement for the 1490-nm signal. At this signal power level, neither stimulated Brillouin scattering nor fiber nonlinearities incur measurable impairment [7, 8]. Our calculations indicate that using the parameters of a deployed fiber, a Raman amplified GPON reach extender of 55-km logical reach and 1:32 split ratio is feasible with class B + specification.

**Table 1. Link loss budget**

	Upstream signal at 1310 nm	Downstream signal at 1490 nm
Tx output power [dBm]	0.5	1.5
50-km feeder fiber loss including splice losses [dB]	18.8	13.8
Loss of 32 way splitter	17.5	17.5
Up to 5-km distribution fiber [dB]	2	1.5
Loss of CWDM combiners [dB]	2	2
Rx sensitivity [dBm]	-28	-27
Total link loss [dB]	40.3	34.8
Gain of optical amplifier [dB]	> 11.8	> 6.3

#### 4. Summary

We have modeled a Raman amplified GPON reach extension system that consists of spliced fiber segments, and calculated numerically, in comparison to a reference fiber, the additional OSNR reductions incurred by the elevated fiber attenuation, splice losses, and splice return losses that are expected of a realistic system. In particular, we have evaluated the performance of such a system using the following parameters: 0.35-dB/km fiber loss at 1310 nm, a splice of 0.05-dB loss and 40-dB return loss every 2 km along the 50-km feeder fiber. The corresponding link loss budget was also provided. It was shown that with B + specification the system is capable of supporting 55-km logical reach (including a 5-km distribution fiber) and 32 ONUs.

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