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Analysis for Designing Cost-effective Optical Access Networks Including Nonlinear Optical Characteristics

Takuya Tsutsumi†, Yu Nakayama‡, Kazuki Maruta§ and Kazuaki Honda†

†neko 9 Laboratories
1–9–7–1015, Kitashinagawa, Shinagawa-ku, Tokyo, 140-0001, Japan
‡Institute of Industrial Science, the University of Tokyo
4–6–1 Komaba, Meguro-ku, Tokyo 153-8505 Japan
§Graduate School of Engineering, Chiba University
1–33 Yayoi-cho, Inage-ku, Chiba-shi, Chiba 263-8522 Japan
Email: tsutsumi.takuya.47a@st.kyoto-u.ac.jp†

Abstract—It is important for telecom carriers to improve cost-efficiency of the optical access networks (OANs) because it occupies the greatest part of network infrastructure cost. To further enhance cost-efficiency, it is useful to improve the acceptable link budget of OANs by using optical amplifiers (OAs), which can increase the splitting ratios and extend the transmission distance of the system. This paper presents a formulation for estimating the total transmission distance of long reach (LR)-OANs in order to quantitatively evaluate the effect of extending the transmission distance on various combinations of splitting ratio with considering nonlinear optical characteristics.

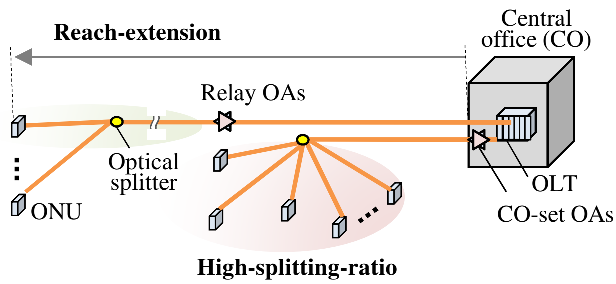


Figure 1: Architecture of LR-OAN.

1. Introduction

The continuous improvement of optical access networks (OANs) develops various application services such as online shopping, video distribution services, and so on. To better support growing these Internet traffics, the reduction of the operational expenditure (OPEX) of OANs becomes more important challenge. The representative cost-effective OAN is the passive optical network (PON) system [2, 3], which provides a cost-effective optical network by sharing an optical line terminal (OLT) with many optical network unit (ONU) [4]. As next-generation OANs, wide-bandwidth PON has been further developed such as next generation (NG)-PON2 and 100 Gb/s Ethernet (100G-E)PON, which are discussed as core technologies for Fifth generation (5G) mobile communication system [1]. With these OANs, telecom carriers desire to cost-effectively accommodate vast amount of Internet traffics while sharing an OLT with many ONUs.

In order to further reduce OPEX, it is effective to apply optical amplifiers (OAs) to OANs so as to increase the shared number of ONUs and extend the transmission distance as shown in Fig. 1. An early enhancement to the access network infrastructure was the long-reach OANs (LR-OANs); it places OAs between the ONUs and central offices (COs) [5, 6]. To create truly effective LR-OAN, it is important to plan how to effectively apply OAs to the LR-OAN while maximizing reductions in OPEX. In terms of planning OAN design, [7] reported the dynamic node integration problem considering declining population over time. However, the nonlinear behavior of optical fiber which causes extra insertion loss and the parameter of the sharing number of ONUs complicates the process of designing OANs to suit actual user distributions. Thus, the accommodation design of a LR-OAN is never comprehensive because the criterion of the transmission distance is not theoretically understood.

In this paper, we target a analysis method that offers flexible network design of LR-OANs as it can estimate the transmission distance given various splitting ratios considering the nonlinear optical characteristics.

2. Nonlinear effects of optical transmission

Fig. 1 shows the fundamental structure of LR-OAN system, which consist of OLT, OAs, ONUs, optical fibers and optical splitters. The span between an OLT and an OA is defined as the trunk span, and the distance between an OA and ONUs are defined as the access span. Upstream and downstream signal are respectively defined as the traveling signal from OLT to ONU and from ONU to OLT, and multiplexed with different wavelength.

Transmission condition in a certain wavelength is simply expressed as the following relationship;

$$L_{tr} + L_{sp} < P - (S + \delta + \epsilon) + G \quad (1)$$

Here, L_{tr}, L_{sp}, P, S, δ and G express the transmission loss, the splitting loss, the optical output power from a laser, the receiver sensitivity of a photo diode, the sensitivity penalty and the optical gain of OAs, respectively. L_{tr} is a linear factor to the transmission distance D and is expressed by the following formulation.

$$L_{tr} = \alpha D \quad [\mathrm{dB}] \quad (2)$$

Following sections introduce nonlinear factors and analyze possible transmission distance.

2.1. Splitting loss

Optical signal of OAN is split by optical splitters for improving the cost-efficiency by sharing an optical fiber and infrastructures among many ONUs. Then, the transmission distance of OAN is nonlinearly changed by the degradation of the optical signal power. The splitting loss is expressed as the following formulation, where N is defined as the splitting ratio.

$$L_{sp} = 10 \log_2 N \quad [\mathrm{dB}] \quad (3)$$

2.2. Optical specification of OAs

The output power from OAs changes nonlinearly to the input power according to the OA's optical specifications. The output power is also controlled with auto level function so that the optical spectrum is not distorted by the gain saturation. Above-mentioned characteristics changes the optical gain of OA's nonlinearly as the function G (P_{in}), in which P_{in} is the optical input power to OAs.

2.3. Chromatic dispersion

When optical signals travel in the optical fiber, the quality of the optical signal is degraded due to its chromatic dispersion. This decreases the optical receiver sensitivity and shortens the transmission distance nonlinearly. The degradation of the sensitivity, δ, is expressed as

$$\delta = -5 \log_{10}[1 - (4BDd\sigma_{\lambda})^2]. \quad (4)$$

B, d and γ indicate the bit-rate, the dispersion coefficient and the root mean square (RMS) width of the optical signal, respectively [8].

2.4. Extinction ratio degradation

OAs generate an asymmetric spontaneous emission (ASE) noise, which degrades the extinction ratio of output optical power [8]. The sensitivity degradation, ϵ, due to the extinction ratio, r_{ex}, which means the power ratio of the off-state signal to on-state signal, is described as

$$\epsilon = 10 \log_{10}\Big(\frac{1 + r_{ex}}{1 - r_{ex}}\Big). \quad (5)$$

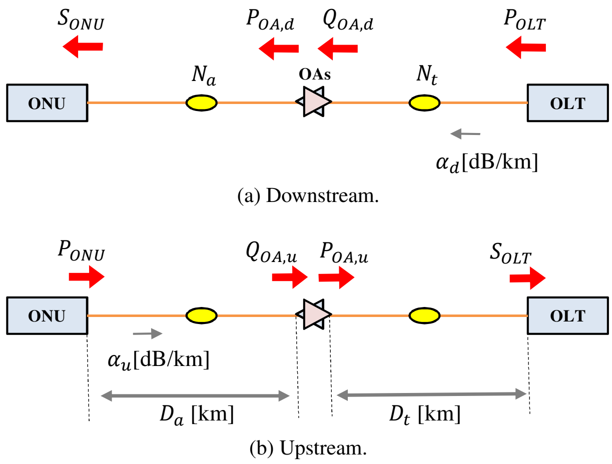


Figure 2: Variables for the calculation.

3. Analysis method of transmission distance

Considering nonlinear effect discussed in previous section, we estimated the total transmission distance, D_{Total} [km], based on the following five simple formulae and parameters as shown in Fig. 2 and Table 1.

$$D_{\mathrm{Total}}(N_{\mathrm{t}}, N_{\mathrm{a}}) = D_{\mathrm{a}} + D_{\mathrm{t}} \quad (6)$$

$$P_{\mathrm{OA,d}}(Q_{\mathrm{OA,d}}) - (S_{\mathrm{ONU}} + \delta_{\mathrm{ONU}} + \epsilon_{\mathrm{ONU}}) \geq \alpha_{\mathrm{d}} D_{\mathrm{a}} + 10 \log_{10} N_{\mathrm{a}} \quad (7)$$

$$Q_{\mathrm{OA,d}} = P_{\mathrm{OLT}} - (\alpha_{\mathrm{d}} D_{\mathrm{t}} + 10 \log_{10} N_{\mathrm{t}}) \quad (8)$$

$$P_{\mathrm{OLT,u}}(Q_{\mathrm{OA,u}}) - (S_{\mathrm{OLT}} + \delta_{\mathrm{OLT}} + \epsilon_{\mathrm{OLT}}) \geq \alpha_{\mathrm{d}} D_{\mathrm{t}} + 10 \log_{10} N_{\mathrm{t}} \quad (9)$$

$$Q_{\mathrm{OA,u}} = P_{\mathrm{ONU}} - (\alpha_{\mathrm{u}} D_{\mathrm{a}} + 10 \log_{10} N_{\mathrm{a}}) \quad (10)$$

Eq. (6) determines D_{Total} by selecting the shorter total transmission distance. Eqs. (7) and (9) represent the transmissible condition, which requires that the optical budget have to exceed the optical loss for upstream and downstream transmission, respectively. Formula (8) and (10) give the input power to OAs for upstream and downstream transmission, respectively. With these formulae, we can exactly estimate the value of D_{Total} with arbitrary parameters.

4. Case study

4.1. Assumptions

Table 2 shows parameters for the calculation of transmission distance. These values are determined based on XG-PON (N1-class) which have been already standardized in [3]. We can also apply other standardized parameters of OAN system.

In this paper, we assumed that the transmission losses of the optical fiber are $\alpha_{\mathrm{d}} = 0.2$ and $\alpha_{\mathrm{u}} = 0.4$ [dB/km] on

Table 1: Variables for the calculation of the transmission distance.

Variable	Definition
D_{Total} [km]	Available total transmission distance.
$D_{\mathrm{t}}, D_{\mathrm{a}}$ [km]	The transmission distance on the trunk and access span, respectively. .
$N_{\mathrm{t}}, N_{\mathrm{a}}$	The splitting ratios on the trunk and access span, respectively.
$\alpha_{\mathrm{d}}, \alpha_{\mathrm{u}}$ [dB/km]	Optical transmission loss per kilometer on downstream and upstream transmission.
$P_{\mathrm{OLT}}, P_{\mathrm{ONU}}$ [dBm]	Average output power of OLT and ONU.
$S_{\mathrm{OLT}}, S_{\mathrm{ONU}}$ [dBm]	Minimum receive sensitivity of OLT and ONU.
$P_{\mathrm{OA,d}}, P_{\mathrm{OA,u}}$ [dBm]	Output power from OAs on downstream and upstream.
$Q_{\mathrm{OA,d}}, Q_{\mathrm{OA,u}}$ [dB]	Input power to optical amplifier on downstream and upstream.
$\delta_{\mathrm{OLT}}, \delta_{\mathrm{ONU}}$ [dB]	Sensitivity degradation by the chromatic dispersion of OLT and ONU sensitivity, respectively.
$\epsilon_{\mathrm{OLT}}, \epsilon_{\mathrm{ONU}}$ [dB]	Sensitivity degradation by the extinction ratio degradation of OLT and ONU sensitivity.

Table 2: Optical characteristics of optical transceivers

Item	Upstream	Downstream
Average output power (min) [dBm]	+2	+2
Receiver sensitivity (max) [dBm]	-27.5	-28
Dispersion penalty [dB]	0.5	1

downstream and upstream, respectively. We also assume that the optical gain and the saturation power of OA is respectively set as 20 dB and +0 dBm for the calculation. When $P_{\mathrm{OA}}(Q_{\mathrm{OA}})$ can be lower than the saturation power, $P_{\mathrm{OA}}(Q_{\mathrm{OA}})$ is increased by the amplification to Q_{OA} with the auto-gain-control. If $P_{\mathrm{OA}}(Q_{\mathrm{OA}})$ can be higher than the saturation power, $P_{\mathrm{OA}}(Q_{\mathrm{OA}})$ is saturated at the saturation power with the auto-level-control. We also assumed that the effect of the sensitivity degradation is negligible in the case.

4.2. Results and discussion

Our analysis approach casts D_{Total} as a two dimensional map with the parameter of the splitting ratio. Fig. 3 shows the D_{Total} map as a function of N_{t} and N_{a}, as estimated by the five formulae. D_{Total} map has the vertical axis of N_{t} and horizontal axis of N_{a}. D_{Total} map provides contours where each curve represents a constant distance. We calculate in two cases OAs, namely, relay OAs ($D_{\mathrm{t}} > 0$ km) and CO-set OAs ($D_{\mathrm{t}} = 0$ km).

Fig. 3a shows the D_{Total} map for OAN without OAs. The map behaves as hyperbolic curve so D_{Total} is constant if the total splitting ratio is the same. D_{Total} is corresponds to 20 km with 32 splits. Fig. 3b, Fig. 3c and Fig. 3d show the D_{Total} contour map for LR-OAN with relay OAs. The contour of Fig. 3b consists of a vertical and horizontal lines due to the saturation by upstream and downstream optical power from OAs. The contour of Fig. 3c consists of the mixture curve of a horizontal line and parabolic curve. D_{Total} with the splitting ratio of (N_t, N_a) = (4, 8) are extended to 63 km from 20 km. From this map, we can also estimate that D_{Total} of $(N_{\mathrm{t}}, N_{\mathrm{a}})$ = (2, 32) and (4, 32) is almost the same, respectively.

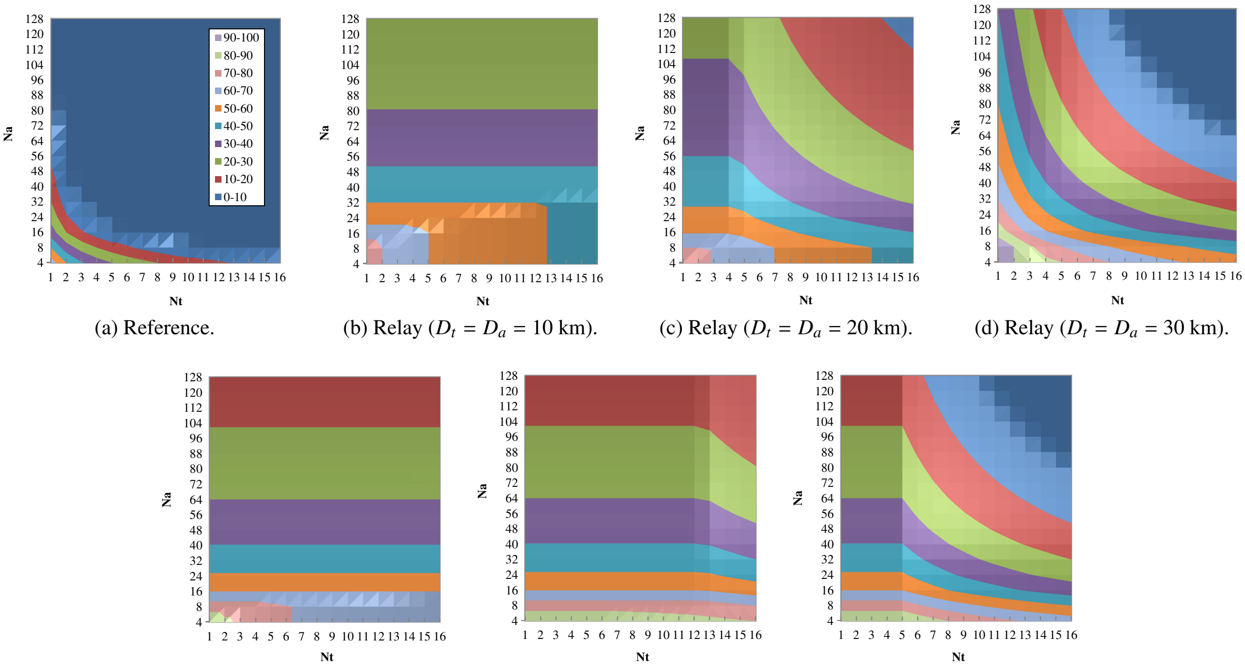
The map of Fig. 3d is expressed by the parabolic curve due to the limitation by upstream transmission. D_{Total} is almost the same in (N_t, N_a) = (4, 8) and (2, 16). If the total splitting ratio ($N_{\mathrm{t}} + N_{\mathrm{a}}$) is constant regardless of the value of N_{t} or N_{a}, D_{Total} is not changed because the downstream power received by ONU remains the same.

Fig. 3e, Fig. 3f and Fig. 3g show the D_{Total} contour map for LR-OAN with CO-set OAs. D_{Total} of CO-set OAs is shorter than that of relay OAs and is limited by upstream signal because upstream optical signal is not amplified on the route of the optical fiber.

We can estimate D_{Total} in other conditions simply by altering the optical characteristics of OAs, OLT and ONU and the optical losses. Thus, we can flexibly design the architecture of an OAN to realize the split-ratio and D_{Total} needed to suit the user distribution. This formulation and design method allows us to easily estimate the D_{Total}.

5. Conclusion

In this study, we proposed the designing methodology which focuses on the factors of the splitting-ratio and the transmission distance. The proposed designing method enables us to estimate the possible transmission distance for an effective deployment of OANs.



(a) Reference. (b) Relay ($D_t = D_a = 10$ km). (c) Relay ($D_t = D_a = 20$ km). (d) Relay ($D_t = D_a = 30$ km).

(e) CO-set ($D_a = 10$ km). (f) CO-set ($D_a = 20$ km). (g) CO-set ($D_a = 30$ km).

Figure 3: Evaluated transmission distance map with splitting ratio of trunk and access span.

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