

Optical Amplifier-Based Multi-Hop Relaying for All-Optical Inter-Satellite Networks

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ABSTRACT

All-optical relaying based on optical fiber amplifiers is a promising approach for realizing high-capacity, low-latency optical satellite networks. By eliminating optical-electrical-optical conversions, such relay systems can reduce power consumption and latency while efficiently supporting wavelength-division multiplexing (WDM) transmission. A key challenge is the degradation of the optical signal-to-noise ratio (OSNR) caused by large free-space coupling losses and the accumulation of amplifier noise over multiple inter-satellite links. This paper presents analytical and experimental evaluations of the transmission performance of all-optical relay systems employing cascaded low-noise amplifiers (LNAs) and watt-class high-power amplifiers (HPAs). Inter-satellite link losses exceeding 50 dB were emulated, and both single-channel and four-channel WDM dual-polarization quadrature phase-shift keying (DP-QPSK) signals at 100 and 200 Gbps per channel were experimentally evaluated. The results demonstrate that 400-Gbps WDM transmission can be achieved over distances exceeding 10,000 km with satellite spacing of approximately 2,000 km. Furthermore, denser constellations with satellite spacing of around 1,000 km enable 800-Gbps-class transmission over similar ranges. These results confirm the feasibility of broadband all-optical inter-satellite networks and provide practical design guidelines for future low-Earth-orbit satellite constellations.

Keywords: LEO constellation, all-optical relay, inter-satellite optical link, free-space optical communication, optical fiber amplifier

1. INTRODUCTION

Low-Earth-orbit (LEO) satellite constellations composed of many small satellites are emerging as a global network infrastructure that can provide wide-area connectivity, low latency, redundancy, and enhanced confidentiality [1-3]. Such constellations are also expected to support resilient communications when terrestrial fiber networks are disrupted, and to serve as relay infrastructure connecting ground stations, geostationary satellites, lunar infrastructure, and deep-space targets. High-speed inter-satellite optical links are essential for realizing broadband optical satellite networks [4-6]. Recent demonstrations of optical inter-satellite links exceeding 100 Gbps between actual LEO satellites have used coherent transceivers and optical fiber amplifiers [7, 8]. In addition, regenerative satellite routing using multiple relay satellites has also been demonstrated. To further enhance link capacity, wavelength-division multiplexing (WDM), which is well established in the fiber communications, is also effective for free-space optical (FSO) inter-satellite links [9, 10]. Figure 1 illustrates the concept of a high-capacity optical satellite network enabled by WDM. In general, regenerative repeaters, which consist of transceivers performing optical-to-electrical (O/E) and electrical-to-optical (E/O) conversion and digital signal processing, together with a high-speed electrical switch, have limited scalability as the number of wavelength channels increases. This is because the number of transceivers required on each satellite grows in proportion to the channel count, as shown in Fig. 2(a). Consequently, power consumption also increases due to the larger number of transceivers and the increased scale of the electrical switching hardware.

On the other hand, as shown in Fig. 2(b), all-optical relay architectures employing optical amplifiers and optical switches offer high scalability for WDM transmission, together with low latency and reduced power consumption. These advantages are particularly important for small satellites, where size, weight, and power consumption (SWaP) constraints are stringent. One of the major challenges in inter-satellite optical links is the large coupling loss caused by beam divergence in long-distance free-space optical (FSO) transmission. In optical fiber communication systems, transmission loss is compensated by optical amplifiers before significant signal degradation occurs, thereby maintaining a high optical signal-to-noise ratio (OSNR) and enabling long-haul transmission. When optical amplifier-based all-optical relays are applied to high-loss

inter-satellite links, the input power to the amplifier becomes extremely low, while amplified spontaneous emission (ASE) noise accumulates over multiple relay stages, resulting in rapid degradation of OSNR. This limits the achievable number of all-optical hops and, consequently, the total relay distance and link capacity. Since degraded OSNR can be recovered by regenerative repeaters, we have also proposed a hybrid relay architecture combining regenerative and all-optical relays, as shown in Fig. 2(c), in which degraded signals are selectively regenerated [11]. Severely degraded signals from ground stations and downlink signals to ground stations can be selectively routed through regenerative repeaters, where their wavelengths can also be converted. Nevertheless, it is important to investigate the maximum number of all-optical relay hops that can be supported over highly lossy inter-satellite links and the corresponding achievable transmission distance.

In this paper, we present both theoretical and experimental investigations of all-optical relays for WDM inter-satellite optical networks. First, we describe the analytical model of the all-optical relay and present the results of OSNR degradation analysis. Next, we demonstrate the transmission performance evaluated using an experimental setup consisting of cascaded low-noise amplifiers (LNAs) and watt-class high-power amplifiers (HPAs).

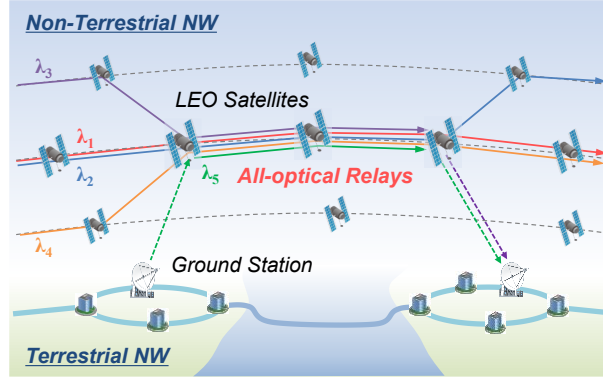


Figure 1. Concept of WDM-based optical satellite networks enabled by all-optical relay technologies.

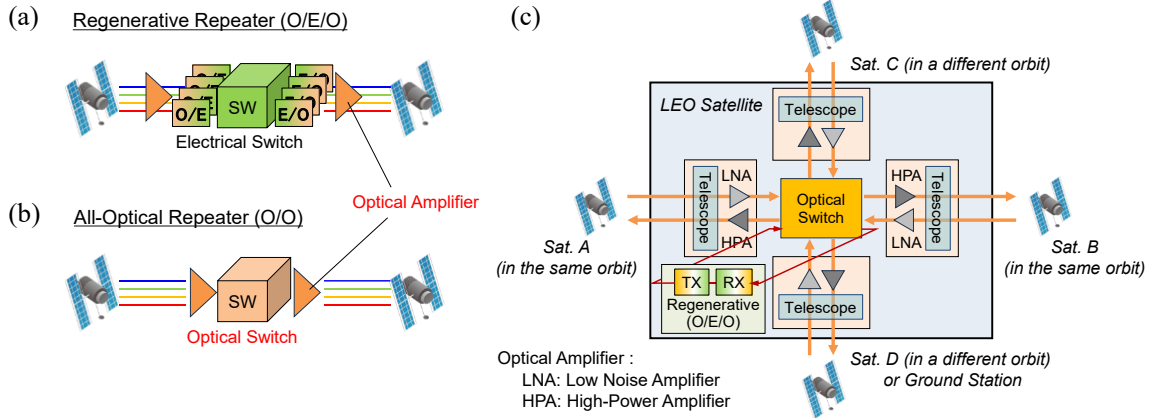


Figure 2. Schematic of (a) a regenerative repeater and (b) an all-optical repeater for the WDM inter-satellite optical relays. (c) Detailed configuration of an all-optical repeater consisting of low-noise amplifiers (LNAs), high-power amplifiers (HPAs), and an optical switch. In a hybrid repeater, only selected wavelength channels undergo O/E/O regeneration, while all other channels are relayed optically.

2. SIGNAL DEGRADATION IN MULTI-STAGE ALL-OPTICAL RELAYING

In long-distance FSO transmission between satellites, coupling loss caused by the mismatch between the expanded beam diameter and the receiver telescope aperture is the dominant attenuation mechanism. For an inter-satellite distance L and wavelength λ , the optical loss (attenuation ratio) Γ is expressed as [12]

$$\Gamma(L) = 2 \left(\frac{\pi D_{TX}}{\lambda} \right)^2 \left(\frac{\lambda}{4\pi L} \right)^2 \left(\frac{\pi D_{RX}}{\lambda} \right)^2, \quad (1)$$

where D_{TX} and D_{RX} are transmitter and receiver telescope aperture gain (diameter), respectively. In this analysis, a small satellite is assumed, with an aperture diameter of 88 mm. Figure 3 compares optical losses in fiber transmission and FSO transmission. Dotted lines indicate power variations in the relay using optical amplifiers. For example, relay intervals are assumed to be 100 km for fiber transmission and 2,000 km for FSO transmission. In the relays for fiber transmission, approximately 20 dB of loss is compensated by an optical amplifier at each repeater, thereby maintaining a nearly constant signal power. In contrast, long-distance FSO transmission over 2,000 km requires compensation for losses exceeding 50 dB using optical amplifiers. To provide sufficient optical power to the receiver and maintain a high OSNR, watt-class optical amplifiers are required at each repeater. Consequently, the optical signal power in all-optical relays, may vary over a wide range from approximately +30 dBm to -30 dBm. The FSO loss represents the unavoidable propagation loss in FSO transmission. In practical systems, additional losses, such as pointing error loss, internal optical loss, and fiber-coupling loss, must also be considered. In this analysis, these additional losses were assumed to be approximately 10 dB and are included in Fig. 3 as the total link loss. Therefore, in this paper, total link losses of -48, -54, -60, and -66 dB are assumed to correspond to inter-satellite distances of 500, 1,000, 2,000, and 3,500 km, respectively.

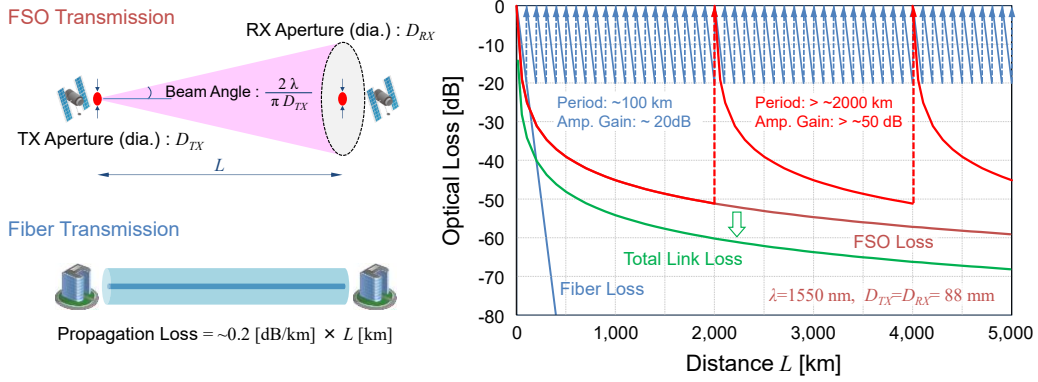


Figure 3. Optical losses in fiber and FSO transmissions at the communication band ($\lambda=1,550$ nm). The FSO loss was estimated using Eq. (1), assuming transmitter and receiver aperture diameters of 88 mm. The dotted lines indicate power variations at the relay nodes. Relay intervals of 100 km and 2,000 km were assumed for fiber and FSO transmissions, respectively. The total link loss of inter-satellite link was assumed to be approximately 10 dB higher than the FSO loss.

The significant link loss in FSO transmission can be compensated using a high-gain optical amplifier, allowing the received signal power to be maintained at an adequate level. However, the OSNR of optical signals degrades with an increasing number of hops (relays). Figure 4(a) presents an analytical model of OSNR degradation. An all-optical repeater in a satellite consists of two low-noise amplifiers (LNA₁ and LNA₂) and one high-power amplifier (HPA). Typically, the LNA and HPA are positioned at the input and output ports of the repeater, respectively. In this model, the optical gains of LNA₁, LNA₂, and HPA are denoted as G_3 , G_5 and G_1 , respectively. The optical losses between HPA-LNA₁, LNA₁-LNA₂, and LNA₂-HPA are represented as Γ_2 , Γ_4 , and Γ_6 , respectively. Γ_2 corresponds to the inter-satellite link loss, including the FSO transmission loss and the additional losses described in Fig. 3. Γ_6 represents internal satellite loss, primarily due to the insertion loss of the optical switch. To compensate for the loss with amplifier gain and maintain a constant signal power, $G_1\Gamma_2G_3\Gamma_4G_5\Gamma_6=1$ (in dB unit, $G_1+\Gamma_2+G_3+\Gamma_4+G_5+\Gamma_6=0$).

After multi-stage amplification and attenuation processes, the number of photons in the signal power N_n and ASE noise A_n are given by:

$$N_n = Y_n N_{n-1} \quad (2)$$

$$= Y_n Y_{n-1} \dots G_1 \Gamma_6 G_5 \Gamma_4 G_3 \Gamma_2 G_1 N_0,$$

$$A_n = (Y_n - 1)n_{sp_n} + Y_n A_{n-1} \quad (3)$$

$$= (Y_n Y_{n-1} \dots G_1 \Gamma_6 G_5 \Gamma_4 G_3 \Gamma_2)(G_1 - 1)n_{sp_1}$$

$$+ (Y_n Y_{n-1} \dots G_1 \Gamma_6 G_5 \Gamma_4)(G_3 - 1)n_{sp_3}$$

$$+ (Y_n Y_{n-1} \dots G_1 \Gamma_6)(G_5 - 1)n_{sp_5}$$

$$\begin{aligned}
& \dots \\
& + Y_n(Y_{n-1} - 1)n_{sp(n-1)} \\
& + (Y_n - 1)n_{sp_n},
\end{aligned}$$

where N_0 is the number of photons in the initial input signal, and Y_n in this equation represents either the optical gain G_n or attenuation (loss) Γ_n . The spontaneous emission coefficient n_{sp_n} is set to zero in attenuation stages ($n_{sp_2} = n_{sp_4} = 0$). The OSNR is calculated as:

$$OSNR_n = \frac{N_n^2}{2 \cdot (N_n + 2\Delta f \cdot A_n + 2 \cdot N_n A_n + 2\Delta f \cdot A_n^2) B} \quad (4)$$

where Δf is the bandwidth of the optical filter, and B is the optical bandwidth [13, 14]. In this analysis, the gains G_3 and G_5 of LNA₁ and LNA₂ were set to +20 dB, respectively, while the gain G_1 of the HPA was set to +37 dB. The inter-satellite link loss Γ_2 was treated as an analysis parameter and set to -48 dB, -54 dB, -60 dB -66 dB and -72 dB. When the noise figures (NFs) of the LNAs and HPA were assumed as 4 dB and 6 dB, respectively, their spontaneous emission coefficients were estimated from $NF_n = 10 \log(2n_{sp_n})$. The parameter settings used in this analysis are shown in Fig. 4.

Figure 5 shows simulated OSNR degradation in the multi-stage amplifications. The OSNR of optical signals degrades with an increasing number of hops. This degradation is highly influenced by the input power to the first amplifier (LNA₁) and its NF. Based on the OSNR requirement at the receiver, the feasible transmission range of all-optical relays can be estimated. For 100-Gbps DP-QPSK signals, an OSNR requirement of 12.5 dB was assumed for signal demodulation [15]. When the inter-satellite link loss is -66 dB, the OSNR falls below this threshold after the six hops. Therefore, the signal must be regenerated at the fifth satellite to restore OSNR. For WDM signals, the OSNR of each channel decreases further due to gain competition among channels. In case of four-channel WDM signals, the OSNR can be 6 dB lower than a single channel case. From another perspective, the OSNR requirement can be 6 dB higher, as indicated by the red dashed line in Fig. 5. When the inter-satellite link loss is -60 dB, the transmission characteristics can be equivalent to those of as single channel and the link loss of -66 dB case. Employing higher-gain HPAs can mitigate significant OSNR degradation at the first amplification. However, the design of all-optical repeaters must also consider the limited power budget available on satellites. In addition, the impact of signal distortions arising from fiber nonlinearities becomes non-negligible.

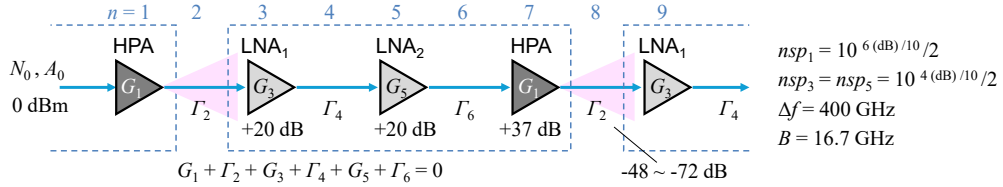


Figure 4. Analytical model of multi-stage amplification and attenuation processes.

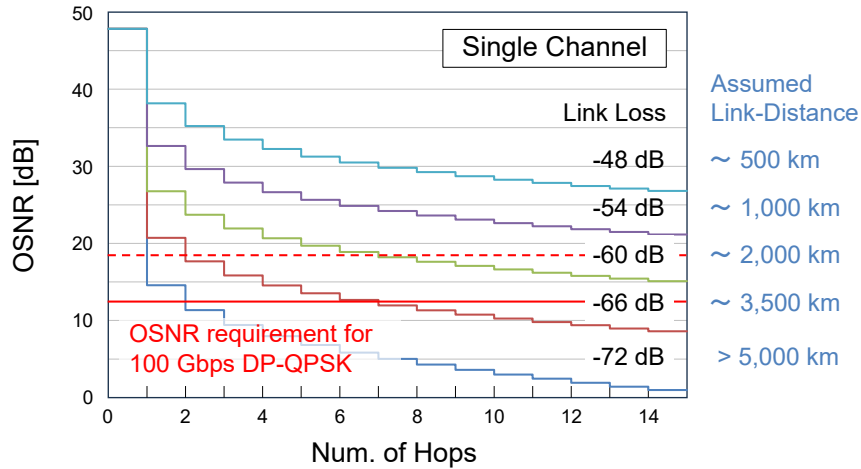


Figure 5. OSNR degradation as a function of link loss for a single-channel (single-wavelength) transmission. The red line shows the required OSNR threshold, as an example, for 100 Gbps DQ-QPSK transmission.

3. EXPERIMENTAL INVESTIGATION OF TRANSMISSION PERFORMANCE

To evaluate the actual transmission performance of all-optical relays under large-loss conditions, six cascaded sets of LNAs and HPAs were prepared to emulate multi-hop relays for inter-satellite optical links, as shown in Fig. 6. As the signal source, four-channel, 100- or 200-Gbps (30- or 60-Gbaud) DP-QPSK signals were used, with a channel spacing of 100 GHz. A wavelength selective switch (WSS) was placed between LNA and HPA, and the signals were extracted from the main transmission line using the WSS and evaluated at each stage. The inter-satellite link-losses were emulated using variable optical attenuators (VOAs). In this experiments, fixed attenuations of 48, 54, 60 and 66 dB were applied by the VOAs, and all VOAs were set to the same attenuation value. The LNAs employed two-stage amplifications, providing a total gain of 43 dB. The maximum output power of HPAs was +37 dBm. Both types of amplifiers were operated at their maximum output power.

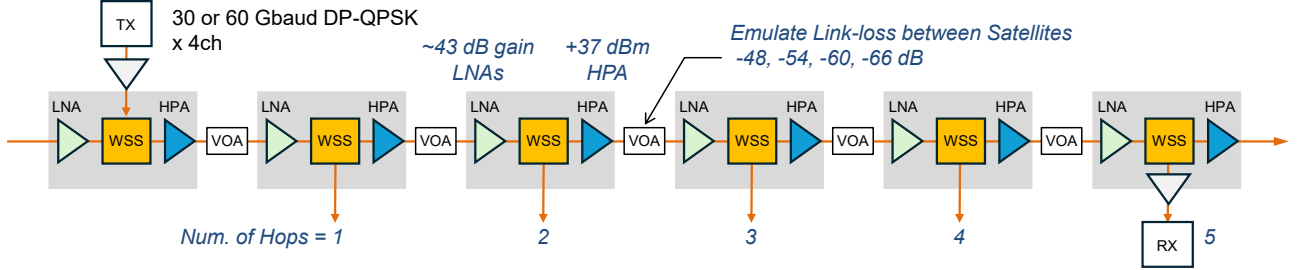


Figure 6. Experimental setup of cascaded LNAs and HPAs. WSSs between amplifiers are used to add and drop the signals. Link-losses between satellites are emulated using VOAs.

Figure 7 shows the optical spectra after each hop for link losses (VOA attenuations) of -48, -54, -60, and -66 dB. Although the signal power is maintained, amplified spontaneous emission (ASE) noise accumulates at each hop, resulting in OSNR degradation as the number of hops increases. A slight inter-channel gain tilt introduced by the optical amplifiers is also observed, becoming more pronounced at longer wavelengths; however, it can be compensated for using a WSS.

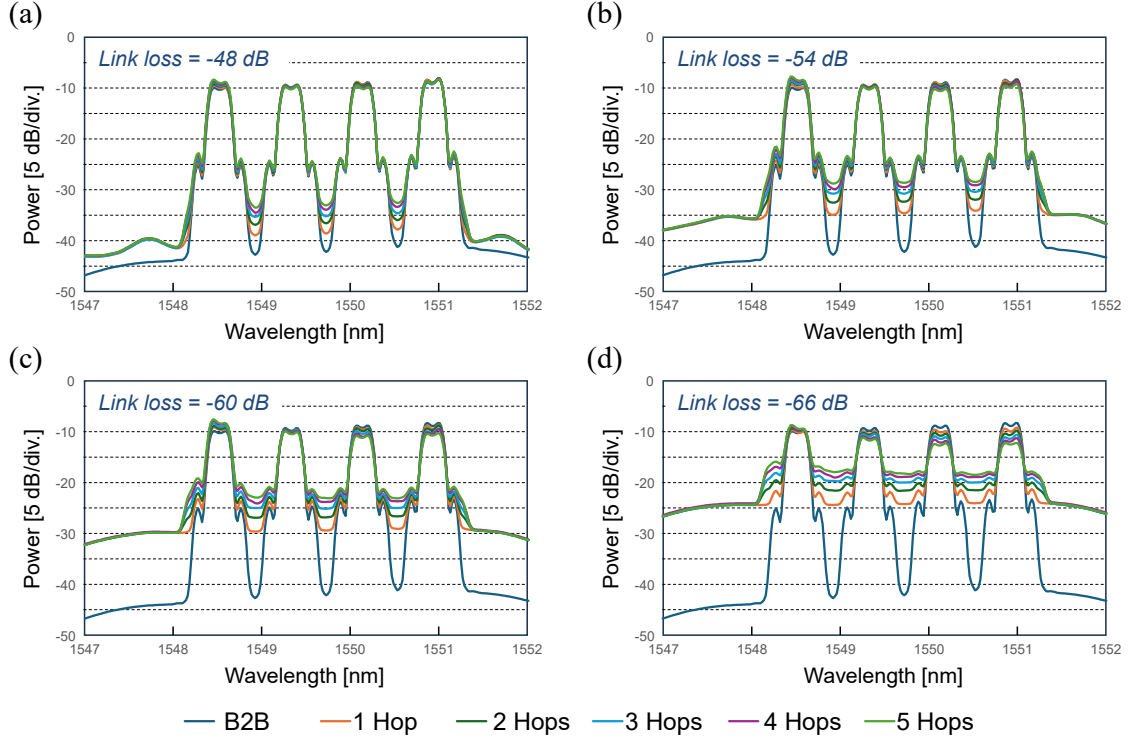


Figure 7. Optical spectra of four-channel all-optical relaying after each hopping at link loss of (a) -48 dB, (b) -54 dB, (c) -60 dB and (d) -66 dB.

Figures 8 show the bit error ratio (BER) characteristics of the signals as a function of the number of hops. In the single-channel case with a link loss of -66 dB, the experiment achieved five hops for 100-Gbps DP-QPSK signals, and three hops for 200-Gbps DP-QPSK signals. These results show good agreement with the hop counts predicted by the analytical results presented in Fig. 5. The OSNR required for 60-Gbaud DP-QPSK is approximately 3 dB higher than that required for 30-Gbaud DP-QPSK. The forward-error-correction threshold was assumed to be a pre-FEC BER of 1×10^{-3} , including a sufficient system margin. Since a link loss of -66 dB corresponds to an inter-satellite distance of approximately 3,500 km, all-optical relay transmission over more than 10,000 km is feasible for both single-channel cases under these conditions.

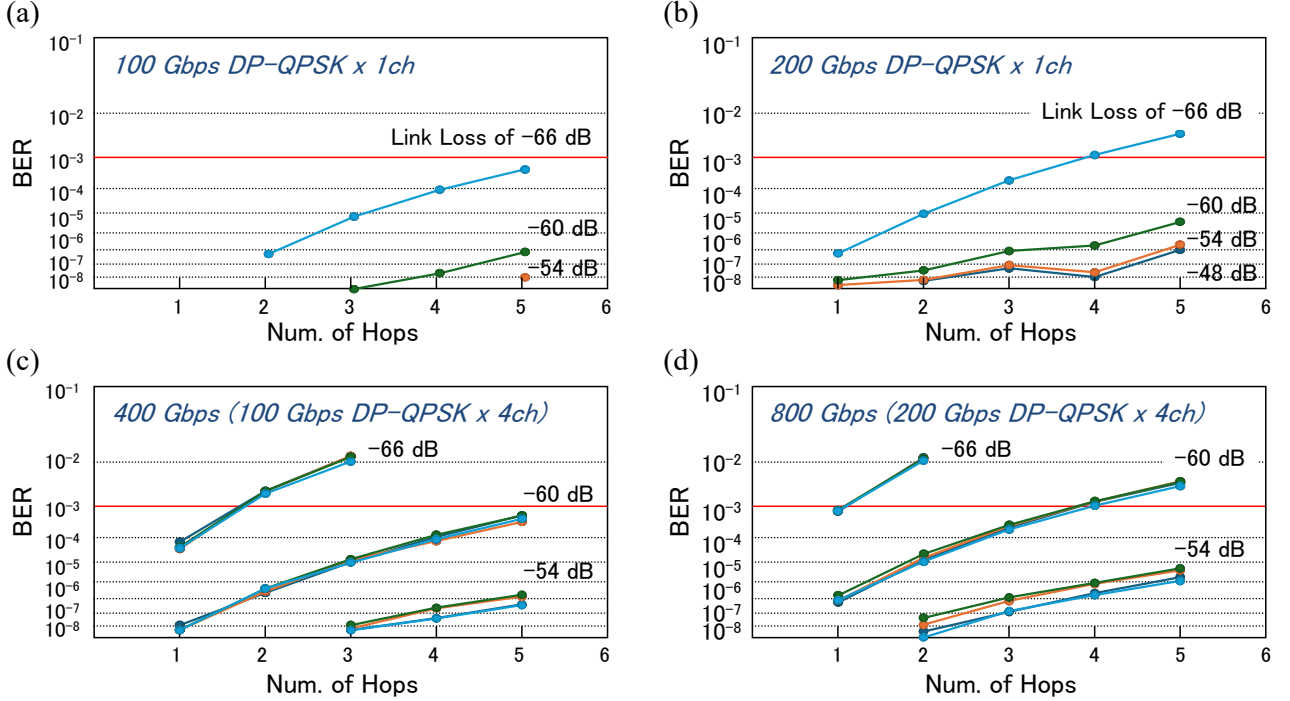


Figure 8. Bit error ratio (BER) as a function of the number of hops for (a) a single channel of 100 Gbps DP-DPSK (b) a single channel of 200 Gbps DP-QPSK, (c) 4 channels of 100 Gbps (400 Gbps) and (d) 4 channels of 200 Gbps (800 Gbps) signals. Link losses of -48, -54, -60, and -66 dB correspond to satellite spacing of approximately 500 km, 1,000 km, 2,000 km, and 3,500 km, respectively.

At a link loss of -60 dB, corresponding to approximately 2,000 km, more than ten hops are expected to be achievable when the OSNR degradation trend is taken into account. This result suggests that all-optical relay design can support long-range optical satellite networks if satellite spacing and amplifier output power are appropriately selected.

For four-channel WDM transmission, the achievable relay distance is more strongly limited by gain competition among wavelength channels. The measured BER characteristics for the -60-dB WDM case were close to those of the -66-dB single-channel case, indicating an effective OSNR penalty due to multi-channel operation. As a result, the achievable transmission distances for 4×100 -Gbps and 4×200 -Gbps WDM signals were estimated to be approximately 10,000 km (by five hops) and 6,000 km (by three hops), respectively, for 2,000-km satellite spacing.

If satellites are deployed more densely, with intervals of approximately 1,000 km, more than ten hops are expected to be possible for both the 400-Gbps and 800-Gbps WDM cases. These results highlight the system-level tradeoff between satellite density, amplifier output power, WDM channel count, modulation speed, and end-to-end relay distance. The above results are summarized in Table 1. The transmission performance beyond six hops was estimated from the analytical results presented in Fig. 5.

The results indicate that all-optical relaying can substantially reduce the need for fully regenerative processing in broadband optical satellite networks. Nevertheless, regenerative repeaters may still be required periodically to restore OSNR after multiple all-optical hops, particularly when the link loss is high or the WDM channel count is large. A hybrid

architecture that combines all-optical relays with selective regenerative repeaters can therefore provide a practical balance among transmission capacity, latency, power consumption, and transmission reach.

An optimal satellite deployment should consider both cost and communication capacity. Wider satellite spacing reduces the number of satellites but increases link loss and OSNR degradation, while denser deployment relaxes the link budget and improves WDM scalability.

Table 1. Estimated total transmission distance of all-optical relaying based on experimental results. Gray-shaded regions represent estimates derived from the analytical results in Fig. 4.

Satellite Spacing		~1,000 km (54 dB Loss)	~2,000 km (60 dB Loss)	~3,500 km (66 dB Loss)
Data Rate	1ch (100 Gbps)	> 10,000 km (> 10 Hops)	> 20,000 km (> 10 Hops)	~17,500 km (5 Hops)
	4ch (400 Gbps)	> 10,000 km (> 10 Hops)	~10,000 km (5 Hops)	~3,500 km (1 Hop)
60 Gbaud DP-QPSK	1ch (200 Gbps)	> 10,000 km (> 10 Hops)	~20,000 km (~10 Hops)	~10,500 km (3 Hops)
	4ch (800 Gbps)	~10,000 km (~10 Hops)	~6,000 km (3 Hops)	~3,500 km (1 Hop)

4. CONCLUSIONS

We investigated all-optical relaying for broadband, low-latency inter-satellite optical networks using cascaded optical fiber amplifiers. Large free-space inter-satellite link losses cause significant OSNR degradation during multi-stage amplification, and this degradation limits the number of achievable all-optical hops. The theoretical model and experimental evaluation show that LNAs and watt-class HPAs can compensate for link losses exceeding 50 dB, but the achievable relay distance depends strongly on input power, amplifier noise figure, WDM channel count, and satellite spacing.

Using cascaded LNA/HPA stages and emulated link losses of -48, -54, -60, and -66 dB, we evaluated single-channel and four-channel WDM DP-QPSK transmission at 100 and 200 Gbps per channel. The results indicate that all-optical relay transmission over more than 10,000 km is feasible. With a satellite spacing of 2,000 km, a 400-Gbps aggregate WDM signal can potentially be transmitted over distances exceeding 10,000 km. On the other hand, by reducing the satellite spacing to approximately 1,000 km, even an 800-Gbps signal can reach 10,000 km. In this fiber-connected emulation of inter-satellite relaying, a fixed loss was used to represent the inter-satellite link. However, the actual inter-satellite link loss is inherently time-varying and may temporarily become larger than the values assumed in this study. As future work, we plan to conduct emulation experiments under dynamically varying loss conditions to more accurately reproduce realistic operational environments.

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