

System Design and Experimental Validation of Inter-Satellite All-Optical Network using a Mid-Scale Satellite Constellation

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ABSTRACT

This paper presents a link-budget-based system design and experimental validation of ISAON for a mid-scale satellite constellation. The analysis considers NeLS, which consists of 120 satellites, and a long-distance transmission route between Tokyo and Los Angeles. The analysis uses an end-to-end received optical signal-to-noise ratio (OSNR) model that accounts for span-dependent link distances in the satellite constellation. The analysis also utilizes laser communication terminal's specifications and four-wavelength WDM transmission with 25-Gbps DP-QPSK signals per channel. The analytical results show that 100-Gbps all-optical relay transmission is feasible in connectable cases. The received OSNR difference between the shortest and longest routes is approximately 2.6 dB, indicating the required OSNR dynamic range for system design. Experimental validation using an optical communication testbed further confirms that the measured OSNR agrees with the analytical result within 0.3 dB and that the BER performance satisfies the OFEC threshold. These results validate the applicability of ISAON to mid-scale satellite constellations.

Keywords: Non-Terrestrial Network (NTN), Inter-Satellite All-Optical Network (ISAON), Low-Earth Orbit (LEO) satellite, satellite constellation, all-optical relay

1. INTRODUCTION

High-speed Non-Terrestrial Networks (NTNs) have been developed with the deployment of Low-Earth-Orbit (LEO) satellite constellations. Optical Inter-Satellite Link (OISL) technology has gathered much attention because it can provide both large transmission capacity and low propagation latency between satellites. Therefore, NTNs, mainly comprising LEO satellite constellations, should be designed by utilizing laser communication links [1].

Large-scale LEO satellite constellations, employing laser satellite links, have rapidly been developed and commercialized worldwide. SpaceX has demonstrated OISLs with a data rate of 200-Gbps class in Starlink [2]. Amazon has also demonstrated 100-Gbps-class OISLs using two prototypes of satellites and is now developing a commercial LEO satellite constellation under Amazon Leo [3,4]. Furthermore, the Space Development Agency (SDA) has been proceeding a LEO satellite constellation for the Proliferated Warfighter Space Architecture (PWSA) and has been standardizing dedicated optical interface specifications [5]. Laser Communication Terminals (LCTs), complied with SDA standards, such as CONDOR developed by Mynaric and SCOT80 developed by TESAT, have also been released [6,7]. Telesat has been aiming at the deployment of Lightspeed as a 10-Gbps-class OISL mesh network [8]. ESA has also been promoting demonstration and standardization of Tbps-class multi-orbit optical networks through HyDRON and ESTOL [9].

In Japan, several companies and organizations have actively been progressing research and development toward LEO satellite constellations, incorporating laser satellite communication. Under the Key and Advanced Technology R&D through Cross Community Collaboration Program, four organizations, including Space Compass, has initiatively been deploying a Japanese satellite constellation employing laser satellite communication links [10]. NTT in collaboration with MBRYONICS, has been developing LCTs equipped with an optical transceiver module implemented with Digital Signal Processor (DSP) chips manufactured by NTT [11]. The National Institute of Information and Communications Technology (NICT) is planning to demonstrate LEO satellite-to-ground laser links utilizing CubeSOTA, a small LCT onboard CubeSats [12].

In this context, NICT has proposed Inter-Satellite All-Optical Network (ISAON) for next-generation NTN [13,14]. ISAON is OISL networks with optical-to-optical (O/O) relay links except for conventional optical-to-electrical-to-optical (O/E/O) regeneration links. This architecture can reduce the processing delay, power consumption, and hardware implementation associated with O/E/O conversion. Furthermore, ISAON has the potential to enhance transmission capacity and enable optical switching and relaying, by introducing wavelength-division multiplexing (WDM).

We have investigated the feasibility of ISAON under the Cutting-edge Research and Development on Information and Computer Sciences (CRONOS) program sponsored by the Japan Science and Technology Agency (JST) [13,14]. In our previous work, we clarified the feasibility of 100/200-Gbps all-optical relay transmission over a 10,000-km-class route corresponding to the distance between Tokyo and Los Angeles, by utilizing our previously developed LCT's specification [14]. We also confirmed the feasibility of 400-Gbps all-optical relay transmission between Tokyo and Los Angeles by extending the LCT's specifications, such as increasing the aperture size of optical antenna and the HPA output power [14]. In addition, we have studied ISAON network operation schemes using satellite orbital information from Starlink [15,16].

However, the feasibility not only for large-scale satellite constellations but also for mid-scale satellite constellations needs to be evaluated to practically deploy ISAON. The large-scale satellite constellations, such as Starlink, can provide shorter inter-satellite distances and enables high data-rate transmissions. Meanwhile, deploying several thousand satellites requires substantial development cost and a long deployment period. Therefore, for early-stage operation and incremental network deployment, it is important to clarify the applicability of ISAON for mid-scale satellite constellations consisting of several hundred satellites.

In this study, we conducted both link-budget-based system design and experimental validation of ISAON, utilizing NeLS, a representative mid-scale satellite constellation consisting of 120 satellites. We assumed a WDM optical signal consisting of four 25-Gbps channels, corresponding to an aggregate transmission capacity of 100 Gbps for a long-distance transmission route between Tokyo and Los Angeles. Under these conditions, we evaluated the applicability of ISAON to the initial operational stage of a mid-scale satellite constellation.

This paper presents a system-level study on applying ISAON to a mid-scale satellite constellation. Section 2 describes the configuration of the ISAON. Section 3 introduces the analytical model for link budget design of ISAON. Section 4 provides the analytical results for the NeLS mid-scale satellite constellation. Section 5 discusses experimental results for ISAON using the testbed. Finally, Section 6 summarizes the paper.

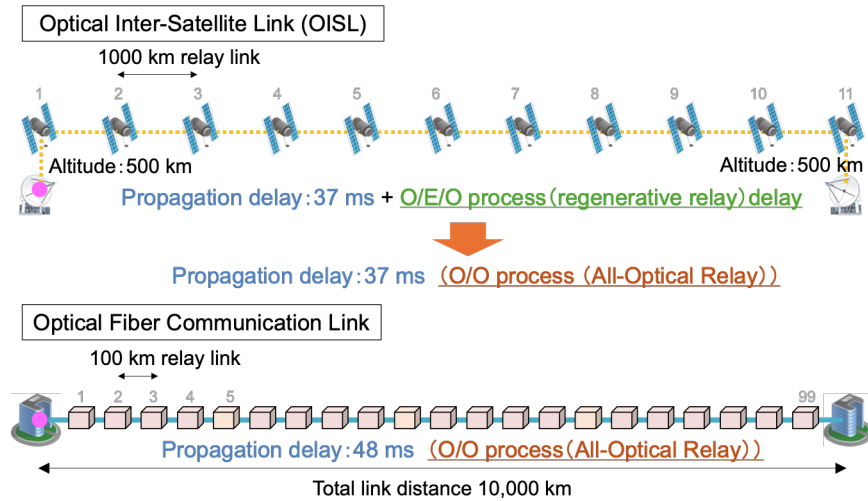


Figure 1. The advantage of the ISAON with all-optical relay links [14].

2. CONFIGURATION OF INTER-SATELLITE ALL-OPTICAL NETWORK (ISAON)

Figure 1 illustrates the advantage of the ISAON with all-optical relay links [14]. Figure 1 assumes a total transmission distance of 10,000 km, with an inter-satellite relay link distance of 1,000 km. In a conventional O/E/O-based regenerative relay network, ten O/E/O regeneration delays are added to the 37-ms propagation delay, increasing the

total system latency. In contrast, the ISAON eliminates O/E/O processing delay, so the latency is mainly limited to the 37-ms propagation delay [14]. Even in an optical fiber network with an inter-node distance of 100 km, the total delay, propagated through the fiber, results in a delay of approximately 48-ms. Therefore, the ISAON enables low-latency long-distance transmission.

Figure 2(a) shows a O/E/O-based relay system implemented in regenerative relay network [14]. In this relay system, optical signals need to be converted into an electrical signal inside the satellite and converted back into the optical signal for routing control. As shown in Figure 2(a), such system is composed of four LCTs for OISLs, LCT for Optical Ground-to-Satellite Links (OGSLs), and a data-processing/routing-control unit. The LCTs for OISLs and OGSLs have a common configuration that implements optical transmitters, optical receivers, a wavelength multiplexer (MUX), a wavelength demultiplexer (DEMUX), a High-Power Amplifier (HPA), a Low-Noise Amplifier (LNA), and an optical assembly subsystem including an optical antenna and a Pointing, Acquisition, and Tracking (PAT) system. However, the received optical signals should be regenerated in the data-processing/routing-control unit and then transmitted to the target LCT, by forward the optical signal to the adjacent satellite. In this regard, the O/E/O -based data-processing/routing-control unit increases the latency, power consumption, and hardware complexity [14].

Figure 2(b) presents a O/O-based relay system implemented in the ISAON. The ISAON performs wavelength-level selection and switching for routing control [14]. As depicted in Figure 2(b), the relay system employs an optical wavelength-selection/routing-control unit including optical switches or Wavelength-Selective Switches (WSSs), an HPA, an LNA, and an optical assembly subsystem. This configuration reduces end-to-end latency, by removing regenerative relay processing. The configuration also reduces the number of optical transmitters, optical receivers, MUXs, DEMUXs, and data-processing/routing-control units, so that it contributes to low Size, Weight and Power (SWaP) [14].

It should be noted that O/E/O-based processing remains desirable for the LCT for OGSL, in consideration of link budget design for OGSL. OGSLs are strongly affected by atmospheric attenuation and turbulence, and the received optical power and signal quality can fluctuate more significantly than those of OISLs [14]. Consequently, the LCT for OGSL requires a data-processing/routing-control unit, an optical transmitter, and an optical receiver. This configuration can establish stable communication links during OGSL connections.

The LCT for OGSL can perform wavelength-level switching of the target wavelengths for Add/Drop process, when forwarding the optical signals from the optical relay system to Optical Ground Station (OGS). In addition, regenerative processing may be required to ensure link feasibility for OGSLs [14]. Therefore, the configuration is effective to add and drop the target wavelengths between the optical wavelength-selection/routing-control unit and the LCT for OGSL. If regenerative relay processing is required at an intermediate point from a link-budget perspective, the data-processing/routing-control unit in the LCT for OGSL can also be utilized in a loopback manner. In this case, it should not be simultaneously used for transmission to the OGS

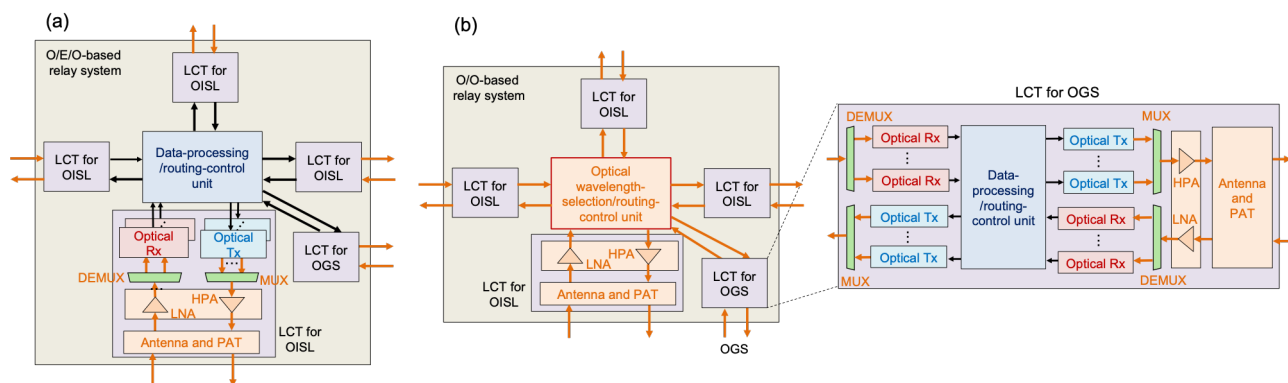


Figure 2. System configuration of (a) O/E/O-based and (b) O/O-based optical relay system [14].

3. ANALYTICAL MODEL FOR LINK BUDGET DESIGN OF ISAON

This section introduces an analytical model of the end-to-end received OSNR for link budget design of ISAON. In our previous works, the received OSNR was calculated, by simplifying assumption that all inter-satellite link distances were equal [13,14]. However, while the intra-plane link distance is almost constant in actual satellite orbits, the inter-plane link distance between adjacent orbital planes varies over time due to the relative motion of the satellites. Therefore, the received OSNR model that accounts for span-dependent link distances should be determined to apply ISAON in the actual satellite orbits.

First, the received optical power per wavelength at each OISL is defined. The received optical power for the i -th OISL is expressed as the Equation (1) [17]. This expression accounts for the free-space propagation loss, transmitter and receiver optical losses, and pointing loss in each span.

$$P_{rx,i} = P_{tx} \cdot a_{tx} \cdot G_{FSO,i} \cdot a_p \cdot a_{rx} \quad (1)$$

The free-space optical gain in Eq. (1) depends on the link distance of each span. Here, P_{tx} denotes the transmitted optical power per wavelength, and $G_{FSO,i}$ denotes the free-space optical gain of the i -th optical link. In this paper, $G_{FSO,i}$ is expressed as Eq. (2) [17].

$$G_{FSO,i} = \frac{1}{8} \cdot \left(\frac{\pi D_{tx} D_{rx}}{\lambda z_i} \right)^2 \quad (2)$$

The Equation (2) is written as the geometrical free-space optical loss calculated from the aperture size of optical antennas, optical wavelength, and link distance. D_{tx} and D_{rx} are the aperture sizes of transmitter and receiver optical antenna, respectively, λ is the optical wavelength, and z_i is the link distance of the i -th span. a_{tx} , a_{rx} , and a_p represent the transmitter and receiver optical loss, and pointing loss, respectively. The HPA output power is expressed as $P_{HPA} = P_{tx} \cdot N_\lambda$, where N_λ is the number of WDM wavelength channels. It is assumed that the optical loss of the optical wavelength-selection/routing-control unit is compensated by the gain of the LNA [18]. The pointing loss a_p is derived using the method reported in [19].

Amplified Spontaneous Emission (ASE) noise accumulated through multiple LNAs is the dominant factor that determines ISAON's system performance. In this regard, the behavior is analogous to multi-span optical amplification in terrestrial fiber-optic communication systems. Consequently, the end-to-end received OSNR is evaluated as the primary metric of ISAON. The received OSNR per wavelength after the i -th LNA is first defined to evaluate the ASE noise generated at each relay stage. The OSNR after the i -th LNA is determined as the Equation (3) [20]. This equation indicates the ratio between the received optical power in i -th span and the ASE noise power generated by the LNA.

$$\text{OSNR}_i = \frac{P_{rx,i}}{P_{sp}} = \frac{P_{HPA} \cdot a_{tx} \cdot G_{FSO,i} \cdot a_p \cdot a_{rx}}{F_n h \nu \Delta \nu_{opt} N_\lambda}, \quad (3)$$

where P_{sp} is the ASE noise power generated after each LNA, F_n is the Noise Figure (NF) of the LNA, h is Planck's constant, ν is the optical frequency, and $\Delta \nu_{opt}$ is the reference bandwidth. Using the received OSNR at each span obtained from the Equation (3), the end-to-end received OSNR is expressed as the Equation (4) [15].

$$\frac{1}{\text{OSNR}_{E2E}} = \sum_{i=1}^{N_A} \frac{1}{\text{OSNR}_i} \quad (4)$$

Therefore, the link feasibility of ISAON can be determined by comparing the end-to-end received OSNR with the required OSNR of the optical transceiver module. Specifically, if the end-to-end received OSNR obtained from the Equation (4) exceeds the required OSNR of the optical transceiver module, the ISAON can be established. Thus, the received OSNR is utilized as a common metric in both the performance analysis in Section 4 and the experimental validation in Section 5.

4. PERFORMANCE ANALYSIS

This section evaluates the characteristics and link feasibility of ISAON for NeLS, which is a mid-scale satellite constellation model consisting of 120 LEO satellites [21]. By using this model, we evaluate the validity of a long-distance transmission route can be established under conditions in which the number of satellites is much smaller than that of a mega-constellation.

4.1 Analytical conditions

Table 1 summarizes the main LCT specifications used for the ISAON link analysis. The target route in this analysis is the Tokyo-Los Angeles transmission route. The optical modulation format is a Dual-Polarization Quadrature Phase-Shift Keying (DP-QPSK) signal with a symbol rate of 8-Gbaud, which enables a user data rate of 25 Gbps per channel. The actual transmitted data rate is 32 Gbps, including the overhead for error correction. we assume an optical transceiver module equipped with a space-grade IOWN DSP chip currently being developed by NTT [22]. The number of WDM wavelength channels is set to four, corresponding to an aggregate transmission capacity of 100 Gbps.

The specifications of the LCT are assumed to be those of LCT, which is previously developed by NICT [23,24]. Specifically, the optical antenna aperture is set to 9.0 cm, the HPA output power to 2.0 W, and the LNA NF to 4.5 dB. The reference bandwidth for OSNR calculation is set to 12.5 GHz, corresponding to the 0.1-nm bandwidth commonly used for OSNR measurements. The pointing error is set to 5.0 μ rad, and the transmitter and receiver optical losses are set to 4.0 dB and 6.0 dB, respectively. The required OSNR for the 25-Gbps optical signal is set to 4.7 dB, based on the back-to-back measurements described in Section 5, using the Open Forward Error Correction (OFEC) threshold of $BER = 2 \times 10^{-2}$ [25].

Table 1. LCT specifications used for the ISAON link analysis.

Wavelength	1550	nm
User data rate	25	Gbps/ch
Transmitted data rate	32	Gbps/ch
Symbol baud rate	8	Gbaud
Modulation scheme	DP-QPSK	
Number of WDM wavelength channels	4	
Aperture size of optical antenna	9.0	cm
HPA output power	2.0	W
LNA noise figure	4.5	dB
Reference band with for OSNR measurement	12.5	GHz
Pointing error	5.0	μ rad
Transmitter optical loss	4.0	dB
Receiver optical loss	6.0	dB
Required OSNR with OFEC threshold of $BER = 2 \times 10^{-2}$	4.7	dB

Table 2 shows the orbital parameters of NeLS used in this analysis [26]. The intra-plane link distance is approximately 4,000 km, and the maximum inter-plane link distance between adjacent orbital planes is approximately 5,000 km in NeLS model. Since these inter-satellite link distances are longer than those in mega-constellations, the feasibility of ISAON needs to be evaluated on the viewpoint of received OSNR.

The transmission route is determined using routing control based on Dijkstra's algorithm. The route candidates include intra-plane links, inter-plane links, and cross links. When the elevation angle is 20 degrees or higher, line-of-sight connectivity is assumed in OGSL. The target period is from 2026-01-01 00:00:00 to 2026-01-01 00:00:51 (UTC), and the Tokyo-Los Angeles transmission route and received OSNR are evaluated over the time interval.

Table 2. Orbital parameters of NeLS used in the link analysis [21].

Satellite constellation type	Inclined orbit	
Total number of satellites	120	
Number of planes	10	
Number of satellites per plane	12	
Inclined orbit angle	55	deg.
Altitude of satellite	1,200	km
Relative spacing between satellites in adjacent planes	1	

4.2 Analytical results

Figure 3 shows the shortest Tokyo-Los Angeles transmission route using NeLS and the link distance of each span. Figure 3(a) shows that the route connects Tokyo and Los Angeles without a large detour using four spans, including OISLs and OGSLs. Figure 3(b) shows that the longest span is the intra-plane link, followed by the inter-plane link between adjacent satellites. The link distances of OGSLs are shorter than those of the OISLs, and the link distances gradually vary with time.

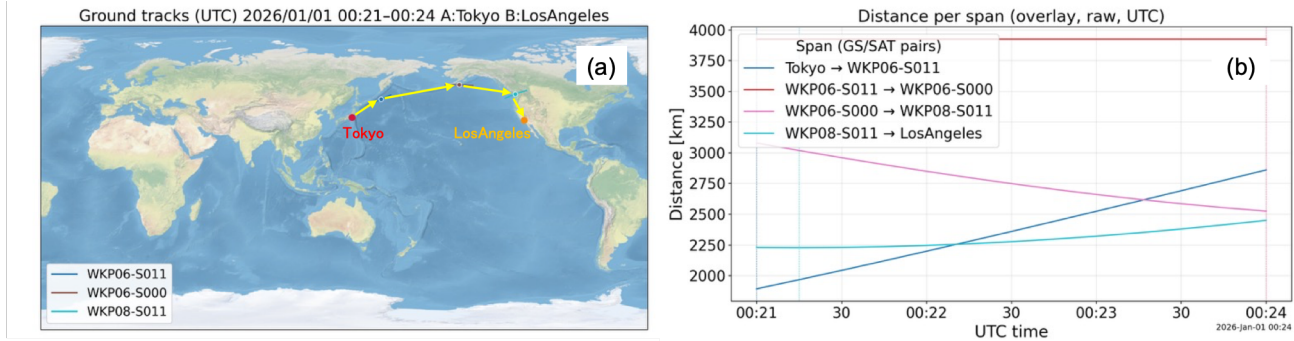


Figure 3. The shortest Tokyo-Los Angeles transmission route using NeLS and the link distance of each span.

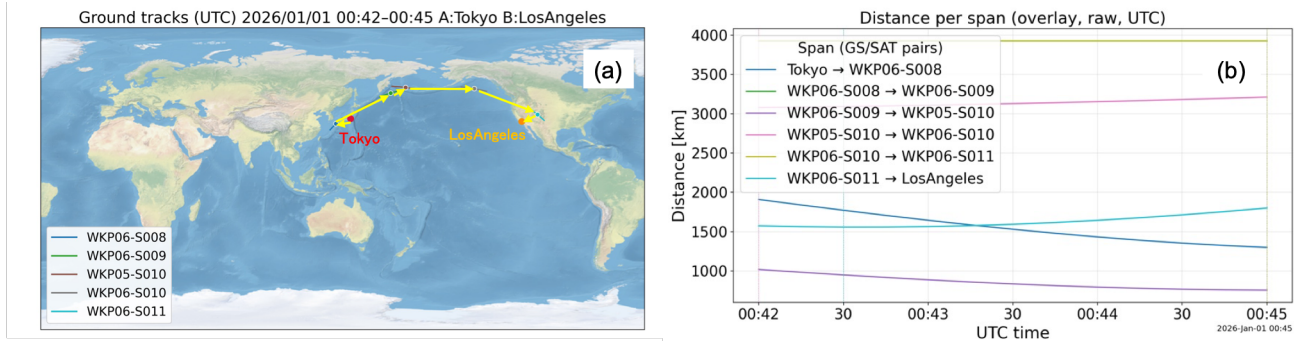


Figure 4. The longest Tokyo-Los Angeles transmission route using NeLS and the link distance of each span.

Figure 4 shows the longest Tokyo-Los Angeles transmission route using NeLS and the link distance of each span. Figure 4(a) shows that the longest route consists of six spans, including OISLs and OGSLs, and forms a detoured route between Tokyo and Los Angeles. Figure 4(b) shows that the two intra-plane links are the longest spans, followed by the inter-plane links between adjacent satellites. The route also includes OGSLs and the shortest cross link. These results confirm the feasibility of ISAON transmission for both the shortest and longest routes, even in NeLS, in which the number of satellites is relatively small.

Figure 5 shows the temporal variation in the received OSNR and total link distance for the Tokyo-Los Angeles route using NeLS model. The total link distance differs by approximately 5,000 km between the shortest and longest routes, which is attributed to the limited number of available route candidates in NeLS. Nevertheless, the received OSNR exceeds the required OSNR in all connectable cases, and the difference of OSNR between the shortest and longest routes is approximately 2.6 dB. Therefore, ISAON system design requires considering the dynamic range of the received OSNR caused by changing route.

Figure 5 also shows that the received OSNR and link distance are absent at some time instants, indicating that a Tokyo-Los Angeles route cannot be found during the periods. This behavior may be caused by the limited number of satellites, which can temporarily result in no satellite being accessible from the OGSs. OISL Connectivity candidates may be secured using intra-plane, inter-plane, and cross links. However, if available OGSL is not found, the transmission route cannot be established. Therefore, additional studies on deployment of OGS, routing control, and link switching are required to establish continuous optical connectivity in meid-scale satellite constellations.

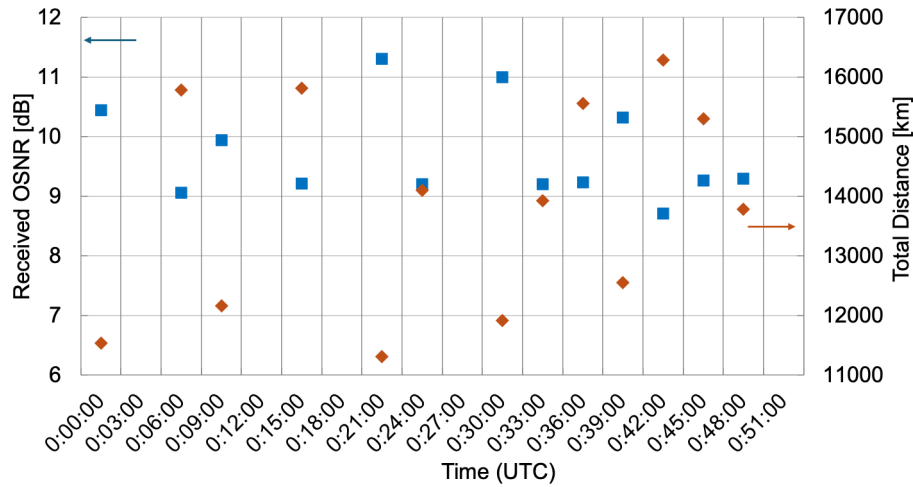


Figure 5. Temporal variation in the received OSNR and total link distance for the Tokyo-Los Angeles route using NeLS model.

5. EXPERIMENTAL VALIDATION

This section experimentally validates the link feasibility of ISAON for NeLS model using an optical communication testbed. Specifically, the shortest Tokyo-Los Angeles route is considered, and the free-space loss of each span and ASE-noise accumulation caused by multi-stage optical amplification are emulated in the laboratory. The received OSNR and bit error ratio (BER) are then measured and compared with the analytical results indicated in Section 4.

5.1 Experimental Setup

In this experiment, all-optical relay transmission along the shortest Tokyo-Los Angeles route is emulated in the laboratory. Each optical link is implemented using a fiber-based variable optical attenuator, a 10-dB optical attenuator that emulates the optical loss inside the LCT, an HPA, an LNA, and a wavelength-selection/path-switching unit composed of a WSS and optical couplers. This configuration reproduces both the received power at each span and the ASE-noise accumulation generated through several LNA. Therefore, the testbed functions can verify the link conditions of ISAON analyzed in Section 4.

The experimental setup is illustrated in Figure 6. The target optical signal is the DP-QPSK signal with a user data rate of 25 Gbps per channel. The actual data rate is 32 Gbps, with the symbol rate of 8-Gbaud including the overhead for error correction. In the WDM configuration, four wavelength channels with 100-GHz spacing in the 1550-nm band are assumed, corresponding to an aggregate all-optical relay transmission capacity of 100 Gbps. At the transmitter, one 32-Gbps DP-QPSK optical signal and three dummy wavelength channels mainly consisting of ASE noise are multiplexed using a WDM multiplexer. The WDM signal is then passed through an HPA that amplifies the optical output, a fixed attenuator that emulates internal optical loss of LCT, a variable optical attenuator that emulates free-space loss, a wavelength-selection/path-switching unit composed of a WSS and optical couplers, and an LNA with an NF of 4.5 dB. The target optical signal is selected at the receiver, and the OSNR and BER are evaluated using a coherent receiver and an optical modulation analyzer (OMA).

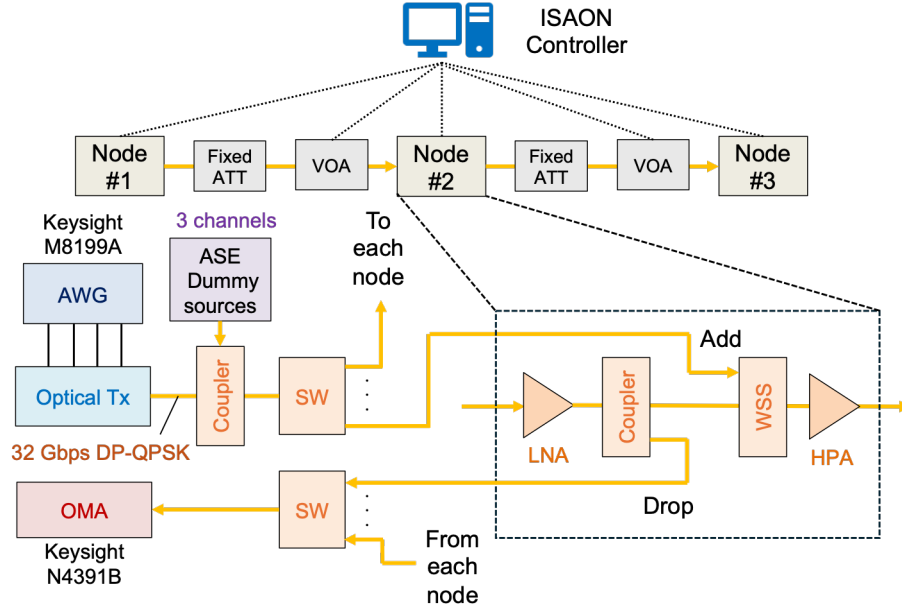


Figure 6. Experimental setup for ISAON using optical communication testbed.

5.2 Experimental results

The back-to-back characteristics of the 32-Gbps DP-QPSK signal were measured to determine the reference of the optical transmitter and receiver used in the experiment. Figure 7(a) shows the OSNR-BER relationship under back-to-back conditions. The back-to-back measurement shows that the required OSNR corresponding to the OFEC threshold of $\text{BER} = 2 \times 10^{-2}$ is 4.7 dB. In this study, the performance is used as the required OSNR for both the analysis in Section 4 and the experimental validation in this section.

Figure 7(b) describes the measured OSNR of the 32-Gbps DP-QPSK signal when the shortest Tokyo-Los Angeles route is emulated. In the experiment, the optical loss for emulating all-optical relay transmission is set using variable optical attenuators. The measured OSNR agrees well with the analytical value, with a maximum discrepancy of approximately 0.3 dB. This agreement confirms the validity of the analytical model of received-OSNR used in Section 4.

Figure 7(c) shows the measured BER and Q-factor values of the 32-Gbps DP-QPSK signal when the shortest Tokyo-Los Angeles route is emulated. First, the Q factors estimated by substituting the analytical and measured OSNR into the back-to-back OSNR-BER characteristics differ by at most approximately 0.3 dB. This small difference shows that the Q factor from analytical OSNR is consistently reasonable with that from measured OSNR. Meanwhile, the Q factor calculated from the directly measured BER differs from the Q factor estimated from the measured OSNR

by at most approximately 0.7 dB. Despite this discrepancy, the measured Q factor remains above the required value corresponding to the OFEC threshold. These results experimentally demonstrate that transmission route can be established in the optical communication testbed.

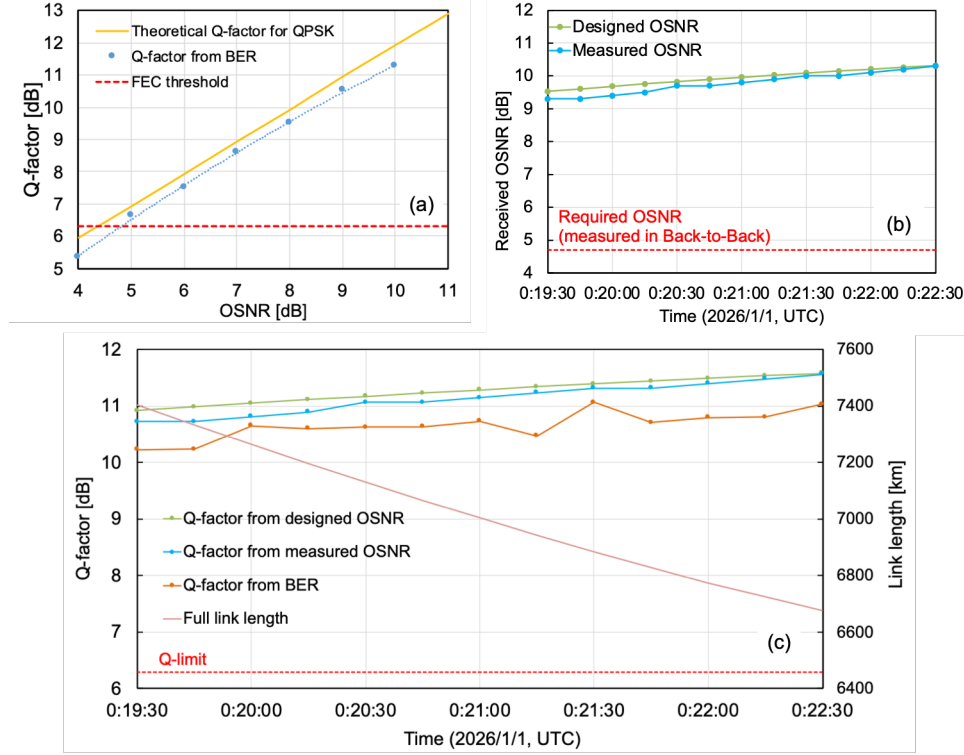


Figure 7. (a) OSNR-BER relationship under back-to-back conditions, (b) measured OSNR for the shortest Tokyo-Los Angeles route, and (c) measured BER and Q-factor values for the shortest Tokyo-Los Angeles route.

6. CONCLUSIONS

This paper reported a system-level study on applying an Inter-Satellite All-Optical Network (ISAON) to a mid-scale satellite constellation. First, the analytical model of the received OSNR was presented by considering span-distance variations in actual satellite orbits. Next, the Tokyo-Los Angeles transmission route was evaluated using NeLS model, which is a representative mid-scale satellite constellation. The results showed that the required OSNR is satisfied in all connectable cases. Furthermore, the analysis also revealed that transmission routes cannot be established during some periods because of the limited number of satellites. This fact highlights technical issues that needs to be addressed to establish continuous optical connectivity. Experimental validation of the shortest route further confirmed that the measured OSNR agrees well with the analytical results and that the BER performance satisfies the required BER threshold. These results demonstrate the validity of ISAON for NeLS model in the optical communication testbed.

Future work will focus on detailed studies toward practical ISAON operation, which is based on the technical issues identified in this study. In particular, routing control that accounts for the intermittency of OGSLs and detailed design of LCT will be essential. By addressing these issues, the feasibility of ISAON applicable to mid-scale satellite constellation can be further enhanced.

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