Impact of Optical ISL on Satellite Routing Path Discovery in LEO Satellite Mega-Constellation

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***Abstract*—The satellite network is one of the key technology of future communications. However, traditional geostationary orbit (GEO) satellite systems have significant problems of a long latency and a heavy launch cost. Hence, low-earth orbit (LEO) satellites have emerged as an alternative system to mitigate the intrinsic problems of GEO satellites. Along with the development of LEO satellite technologies, the inter-satellite link (ISL) has been designed to provide improved system performance and more reliable service. In addition, the optical ISL has been highlighted due to its high data rate and small terminal size. In this study, we consider the mega-constellation architecture, time-varying satellite topology, and multiple visible satellites. The impacts of optical communications are investigated on the routing path discovery procedure. Then, we propose a routing algorithm and compare the system performances of RF and optical systems.**

Keywords— LEO satellite mega-constellation, time-varying satellite topology, inter-satellite link (ISL), optical communication, packet transmission, satellite routing

I. Introduction

Traditional satellite systems have mainly performed a secondary role for terrestrial systems through the signal relaying with geostationary (GEO) satellites [1]. Currently, satellite communications become a core technology of future communications such as the 5G non-terrestrial network (NTN) and 6G network. Satellite systems can support geographical connectivity coverage and effectively complement a dense terrestrial network [2],[3]. Even though various advanced GEO satellite communication technologies have been developed, existing GEO systems have critical problems of very long latency and its heavy installation cost. In response to these issues, low-earth orbit (LEO) satellites are now being highlighted as an attractive system because they can provide much less latency and lower cost. However, due to the small footprint of LEO satellites, more than hundreds of satellites are required for supporting global coverage. Hence, companies such as SpaceX [4] and Amazon [5] have developed mega-constellation architectures (Starlink/Kuiper).

In addition, researchers have attempted to utilize optical inter-satellite links (ISL) for high performance and reliable services [6]. The feasibility of optical ISL was analyzed in an effort to determine the advantages of the shortened link distance of mega-constellation architectures [7]-[9]. However, due to the very short wavelengths (700-1600 nm) of optical systems [10], it has very narrow beam divergences and requires highly accurate beam alignment. The requirement of precise beam alignment affects the end-to-end (E2E) routing as an additional delay within the reliable link establishment process. Accordingly, we concentrate on routing path discovery in the mega-constellation with optical ISL. The concept of satellite routing is illustrated in Fig. 1.

However, conventional studies have several problems with regard to visibility models among neighboring satellites and routing algorithms. While the periodic and predictable characteristics of the LEO satellite topology were utilized in some studies [11]-[13], they only addressed the Manhattan street network (MSN) for the satellite visibility, which is a typical model with a single visible satellite in each direction of front, rear, left and right from a satellite. The Iridium (66 satellites) used this for the constellation model. A two-step routing process was exploited with series of topology snapshot information [14]. The E2E routes of all snapshots were computed by the Dijkstra's algorithm [15]. Then, an optimal path was calculated to reflect the topology variation over time due to the movement of the LEO satellites using derived routing paths for the topology snapshots. In [16],[17], the searching region was restricted and the path was discovered by Dijkstra's algorithm with the

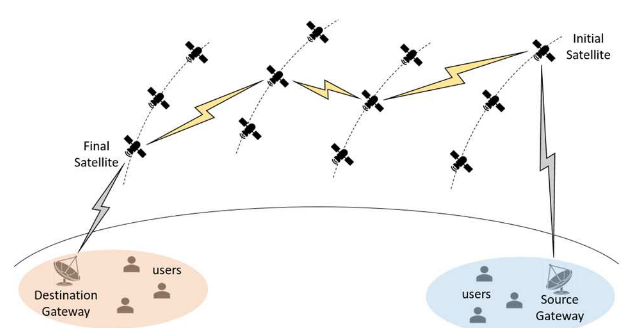

Fig. 1. Concept of LEO satellite routing with optical ISL in mega constellation.

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queuing delay. The main challenges of prior studies are the small constellation model and the single visible satellite condition. In addition, although researchers have addressed both the mega-constellation and topology variation [18]-[20], the system performance were scrutinized for only hop counts and the link distance with the MSN structure.

Hence, in this article, we focus on the impact of optical ISL and propose a satellite routing algorithm with the multiple visible satellite model in the mega-constellation, of which the visibility model was proposed in our last study [21]. The MSN structure has the advantages of being easy to find connecting neighboring satellites (fixed connectivity) and simple link maintenance. However, although a satellite can connect to multiple visible satellites in the mega-constellation architectures, the MSN design leads to inefficient results due to the single satellite visibility [22]. In addition, the recent developments of the phased array or steerable antenna are expected to enable more reliable and accurate link connections with several neighboring satellites.

The rest of the paper is organized as follows. Section II describes the impact of optical communications in ISL for additional delay components. In section III, we introduce the satellite constellation model, satellite selection method according to which the satellite connects to the gateway, and the packet transmission scheme. In Section IV, the proposed routing algorithm is explained. In Section V, the simulation results are provided in terms of the E2E latency and hop counts. The conclusions are presented in Section VI.

II. Impact of Optical Communication on ISL Connections

Optical communication systems have several advantages, including high directivity, small antenna size, less power/mass requirements, and unlicensed spectrum due to the short wavelengths (700-1600 nm) [6]. In addition, the extremely high bandwidth enables these systems to support 10^5 times higher channel capacity than RF systems. However, very accurate beam alignment must be provided in ISL connections due to the exceedingly narrow beam divergence of optical communication systems [10]. Hence, precise beam pointing and beam scanning are required for the reliable link establishment between adjacent satellites. However, these are influenced on the E2E routing path discovery process, as new latencies which are the beam pointing error compensation time and beam scanning time. These latencies are caused by the pointing, acquisition and tracking (PAT) procedure related to the establishment of a reliable optical link. First, the beam pointing error θ_{pe} is caused by the satellite's jitter and is defined by the Rayleigh distribution [9],

$$f(\theta_{pe}) = \frac{\theta_{pe}}{\sigma_{pe}^2} \exp\left(-\frac{\theta_{pe}^2}{\sigma_{pe}^2}\right), \tag{1}$$

where σ_{pe} is the standard deviation of the beam pointing error. The pointing error must be addressed for a clear optical link connection. Accordingly, to compensate for the beam pointing error, we utilize only the optical antenna's rotating capability κ_r (rotation speed). The pointing error compensation time T_{pec} can be calculated by θ_{pe}/κ_r with $\kappa_r = 30$ deg/s. The pointing error compensation time is summarized in Table I to depend on the average pointing errors over the standard deviations. Intuitively,

TABLE I
AVERAGE POINTING ERROR AND COMPENSATION TIME

σ_{pe}^2	1	1.5	2	2.5	3
θ_{pe} (rad)	1.265	1.541	1.771	1.977	2.159
T_{pec} (ms)	2.405	2.942	3.396	3.817	4.168

with an increase in the standard deviation, the pointing error compensation time also increases. In an analysis of the impact of optical communication, we exploit the parameter of the Rayleigh distribution for which $\sigma_{pe}^2 = 1$. Beam scanning is used to search for uncertainty areas to locate and establish a link with a connectable adjacent satellite. The beam scanning time can be computed as follows:

$$T_{scan} = \frac{2\pi\sigma_{pe}^2}{I_{beam}^2}\left[1 - \left(\frac{\theta_U^2}{2\sigma_{pe}^2} + 1\right)\exp\left(-\frac{\theta_U^2}{2\sigma_{pe}^2}\right)\right] \cdot T_{dwell}, \tag{2}$$

where $I_{beam} = \theta_{div}(1 - F_0)$ denotes the step length related to the beam divergence angle θ_{div} and overlap factor F_0. $T_{dwell} = T_R + 2\,d/c$ is the dwell time, where d is the link distance, c is speed of light and T_R is the response time of the receiver system. θ_U is the size of the uncertainty area. We use a 0.1 m antenna, 0.2 as the overlap factor and 200 Hz of the response time of the bandwidth of the fine pointing control system with a 1550 nm wavelength. The analyzed beam scanning time is depicted in Fig. 2. As the standard deviation and link distance increase, the scanning time also increases due to the influence of increased pointing error. Accordingly, we can verify that the standard deviation of the beam pointing error affects (1) and (2). Therefore, the influences for each delay factor are analyzed as a fraction of the latency according to the link distance, for which the results are illustrated in Fig. 3. Especially, in Fig. 3(a), beam pointing error compensation time T_{pec} accounts for the considerably large fractions of about 30-70% depending on the standard deviation at a link distance of 500-1500 km (most often used with the mega-constellation). In Fig. 3(b), the faction of beam scanning time T_{scan} is smaller than that of T_{pec}, but the influence of the T_{scan} cannot be neglected in the LEO satellite routing. In spite of these additional latencies, the mega-constellation has the advantage of relatively low latency with a

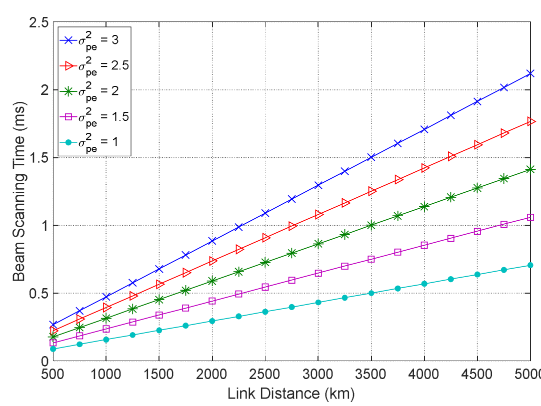

Fig. 2. Beam scanning time over link distance and standard deviation of pointing error.

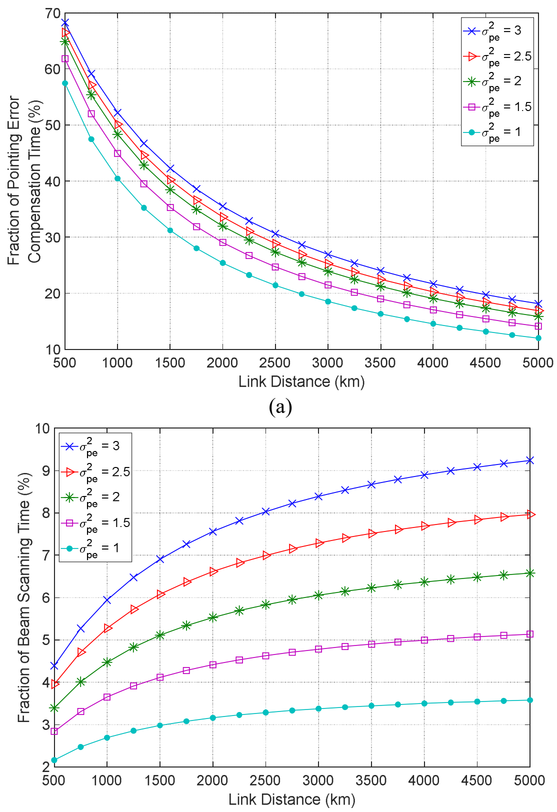

Fig. 3. Impact of the standard deviation of the pointing error for (a) fraction of pointing error compensation time and (b) fraction of beam scanning time.

shorter distance than the traditional LEO satellite topology. Therefore, we address the two delays in the routing path discovery in the LEO satellite mega constellation as the optical link connection latency.

III. System Model

In this section, we describe the system model for the satellite constellation, the satellite selection method connected to the ground gateway and the packet transmission scheme used in the satellite routing path discovery process.

A. Satellite Constellation

In this subsection, we explain the LEO satellite constellation architecture. Typically, satellite constellations can be divided into two types according to the orbital eccentricity. These are a circular orbit ($e = 1$) and a non-circular orbit ($0 < e < 1$). For reliable satellite communication services with global coverage, it is important to exploit the satellite constellation with the circular orbit model that can provide a stable ground-satellite connection with a similar link distance despite satellite movements and the oblateness of Earth. In general, there are two popular LEO satellite constellation designs that are used with the circular orbit: the Walker-delta pattern and the Walker-star pattern [23],[24]. In this paper, we exploit the Walker-delta constellation model as a LEO satellite network. The Walker-delta model is expressed as $i^{\circ}:S/P/f$, where i denotes the inclination of the orbital plane, S is the total number of satellites, P is the number of equally spaced planes, and f is the relative spacing between satellites on adjacent planes. The change in the true anomaly (in degrees) for equivalent satellites on neighboring planes is equal to $f \cdot 360/t$. An advantage of the Walker-delta model is that the neighboring satellites move in the same direction, each in its own orbital. Besides, satellites are located in the regions where there are lots of data transfer and service requests. We assume that a satellite has four optical antennas that can connect with satellites in the front and rear of the same orbital plane and on the closest adjacent orbital planes to the left and right, respectively. The parameters of the satellite constellation are summarized in Table II.

TABLE II
PARAMETER OF LEO SATELLITE MEGA CONSTELLATION MODEL

# of Satellites (S)	1600
# of Orbits (P)	32
Inclination (deg)	53.8
Altitude (km)	1000

B. Satellite Selection

Satellite selection refers to a method of selecting the satellite connected to the gateway, GW. We use two satellite selection methods for efficient data transmission: 1) the minimum distance satellite S^{MD} selection and 2) the longest connectable satellite S^{LC} selection methods.

1) Minimum distance satellite S^{MD} selection: The gateway GW simply selects the closest satellite when there is a data transfer request. This method has the advantage of a very straightforward design, but one problem is that connected satellites change frequently due to topology variations.

2) Longest connectable satellite S^{LC} selection: This method serves to select a satellite that can be connected to the gateway GW for a long time. The S^{LC} selection approach is depicted in Fig. 4. When using the S^{LC} selection method, the gateway GW initially finds visible satellites (blue cross) under the antenna elevation constraint ($\theta_{ele} \geq 10$). Second, among the visible satellites, they are classified according to how they move in the direction with an increasing value of θ_{ele}. Lastly, among the distinguished satellites (red dot), the satellite (orange circle) with the smallest θ_{ele} among the distinguished satellites located in the same orbital plane with S^{MD} (green square) is selected. The same selection method is applied to both the initial satellite

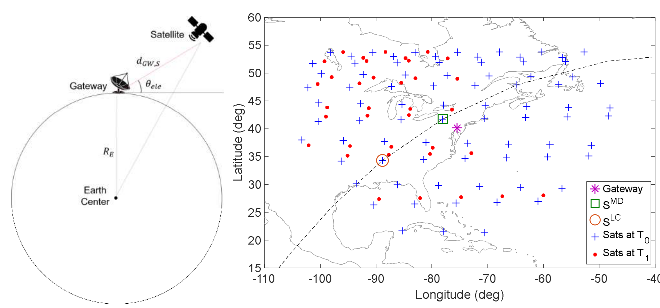

Fig. 4. Longest connectable satellite selection.

(IS) and final satellite (FS) decisions. The selected satellites can be changed due to topology variations caused by the latency in data transmission.

The selected satellite is connected until it is not visible to the gateway, and the gateway re-searches before disconnection to provide stable services.

C. Packet Transmission

The satellite network has a time-varying topology due to the movement of the satellites. When transmitting data from the source to the destination, the topology may change before data transmission is complete due to the latency caused by the data size and the link distance. Therefore, we consider not only the propagation delay by the link distance but also the packet transmission time between nodes to reflect the time-varying satellite topology property. The packet format is exploited to the IP protocol with the standard of the Consultative Committee for Space Data Systems (CCSDS) [25] and the generic stream encapsulation (GSE) protocol in the DVB standard [26], for which the formats are shown in Fig. 5. In the analysis of the system performance, the propagation delay (d/c) and packet transmission time (l_p/R) are considered, where l_p is the packet length and R is the data rate, which is the supportable channel capacity of RF and the optical communication terminal within LEO satellites. In optical systems, the aforementioned additional latencies are also applied. Then, for the packet transmission scheme, simple consecutive packet transmission is used, as shown in Fig. 6. We assume that the packets are transmitted when the previous packet reaches the next node.

IV. Satellite Routing Path Discovery

In this section, we propose a satellite routing algorithm under the continuous LEO satellite topology variation. The proposed routing algorithm is depicted in Fig. 7. The properties of the periodic and predictable LEO satellite topology are utilized and next node determination focuses on the path searching procedure. A centralized approach is used, in which the end-to-end path is computed on the ground.

First, the source and destination gateways determine the initial satellite IS and a final satellite FS to be connected to according to S^{MD} and S^{LC} at the every routing path searching instance, respectively. A routing path is discovered from IS to FS using Dijkstra's algorithm with multiple visible satellites when data transmission is requested. Specifically, the FS is determined at every routing path discovery instance to ascertain the sustainability of the discovered path. Then, we focus on the determination of the next node. For example, the path p_1 is initially searched between IS and FS at T_1 using Dijkstra's algorithm. The second satellite $p_1(2)$ becomes the starting node in next discovery process and path p_2 from the starting node $p_1(2)$ to the FS is discovered at T_2. Before repeating the path discovery, we check the availability of the same FS at T_2. If the FS is not available, the FS is updated. The discovery instance considers the data transmission latency (from $p_k(1)$ to $p_k(2)$) from the prior path discovery point. This process is performed repeatedly until the starting node and the final satellite are identical. The proposed routing path discovery algorithm is presented here as **Algorithm 1**.

In this algorithm, we examine FS availability as the topology changes to ensure efficient E2E data transfers and continuity of the discovered routing path. If the same FS can be exploited for two adjacent packets, it is determined that the same route is available for them. In this case, only the propagation delay and data transmission time in the last link of the E2E routing path make a difference for E2E delay calculation. We expect to reduce the overhead in terms of delay caused by link establishment in the optical ISL by using the same route between adjacent packet transfers. On the other hand, if the same FS routing path is not available, we judge that path reuse is impossible, and should find a new FS and re-search the path.

V. Simulation Results

We evaluate E2E data routing in the LEO satellite mega-constellation through a comparison with the RF system and optical communication in the ISL. The ground-satellite connection is assumed to use the RF link only. Due to the additional latency of optical communication, as described in Section II, we address not only the propagation delay and the packet transmission time, but the pointing error compensation time and beam scanning time in optical ISL. In addition, the system performances are evaluated for both satellite selection methods in Section III-B. For E2E routing path discovery, we

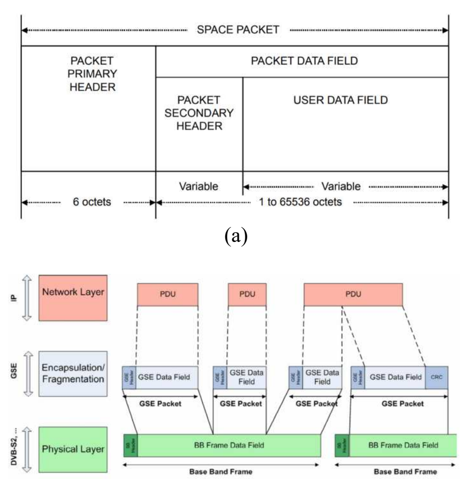

Fig. 5. Packet format of (a) CCSDS [25] and (b) GSE protocol [26].

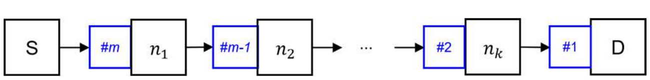

Fig. 6. Packet transmission scenario.

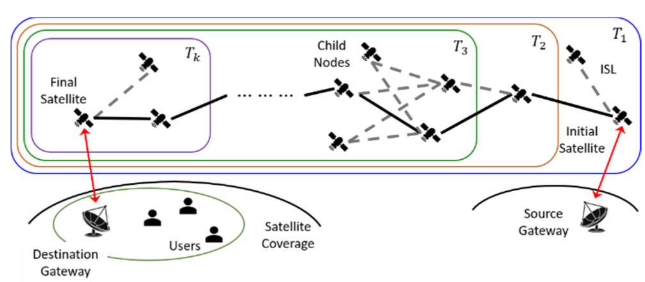

Fig. 7. Concept of iterative satellite routing path discovery algorithm.

Algorithm 1 Iterative Satellite Routing Path Discovery

Input: $IS(T_1)$, $FS(T_1)$ and $k = 1$
$Length_{pkt} =$ [10 250 1000 2500]
Satellite Visibility Matrix
Output: ISL E2E Routing paths RP

for $i = 1 : Length\_pkt$ **do**
  while $IS_i(T_k) \neq FS_i(T_k)$ **do**
    Compute Path p_k by Dijkstra's algorithm at T_k
    $RP_i(k) = p_k(1)$
    $k++$
    $T_k = T_{k-1} + ISL\_Delay(p_k(1), p_k(2))$
    $IS_i(T_k) = p_{k-1}(2)$
    Compute $FS_i(T_k)$
    if $FS_i(T_k) \neq FS_i(T_{k-1})$ **do**
      Update $FS_i(T_k)$
    end if
  end while
end for

assume that the locations of the source and destination gateways are Seoul (37.34 N/126.59 E) and New York (40.42 N/74.00 W). We also assume that the maximum length (63553 bytes) of the data field in the packets is transmitted, including several headers of GSE and Internet protocol. We assume that 10, 250, 1000 and 2500 packets are transmitted according to the data type. For instance, 10 packets case denotes a text file and 2500 packets case is a video file. We analyze system performances for four evaluation indices. First of all, the representative metrics of hop counts and E2E latency are investigated. Then the average number of iteration in a path discovery attempt is inspected as Algorithm 1 of Section IV has an iterative search process to find one routing path for packet transmission. Finally, due to the topology variation, multiple path discoveries are required while a large number of packets are transmitted. We assess the average number of path discovery attempts required to transmit all the packets. The simulation results are summarized in Tables III and IV according to the satellite selection methods of S^{MD} and S^{LC}, respectively. In the comparison between RF and optical ISL in both the S^{MD} and S^{LC} conditions, with the small number of packets (10 packets), the RF ISL environment has a lower average ISL E2E delay and smaller average number of path discovery attempts than those of optical system. On the other hand, as the number of packets increases, the performance of the optical ISL condition is better than that of the RF system about 8 % in terms of the latency and discovery attempts. The low latency of optical ISL will be a major advantage in the communication industry of the future for large data transmissions and real-time transmissions such as image data transmission or vehicle-to-everything (V2X) communications. In a comparison between the S^{MD} and S^{LC} methods, the average number of discovery attempts by the S^{LC} method surpasses that of the S^{MD} method by up to 52 % in RF systems and 46 % in optical systems at 2500 packets, respectively. If another extra delay occurs when selecting a satellite connected to a gateway or performing a handover for stable services, we can expect that the S^{LC} method will show much better E2E delay performance than that of S^{MD}. However, very similar system performance outcomes were noted in terms of the average hop counts and average number of iterations in a discovery attempt for the RF or optical systems and satellite selection methods.

VI. Conclusion

In this paper, we propose a satellite routing path algorithm under the time-varying LEO satellite topology to supplement the system models in prior studies, which only consider the link distance. First, we analyzed the impact of the optical ISL system,

TABLE III
SIMULATION RESULTS OF S^{MD} METHOD

	RF ISL (10 mm)				Optical ISL (1550 nm)			
# of Packets	10	250	1000	2500	10	250	1000	2500
Avg. Hop Counts	22.035	22.434	21.437	21.414	19.773	22.429	21.929	21.701
Avg. ISL Delay (ms)	139.768	940.897	4204.219	10351.407	143.954	902.088	3689.726	9390.822
Avg. # of Iterations	22.046	21.636	18.788	18.627	19.773	21.625	19.995	19.379
Avg. # of Attempts	1.000	2.712	10.530	26.760	1.000	2.410	9.692	24.132

TABLE IV
SIMULATION RESULTS OF S^{LC} METHOD

	RF ISL (10 mm)				Optical ISL (1550 nm)			
# of Packets	10	250	1000	2500	10	250	1000	2500
Avg. Hop Counts	20.276	21.977	21.623	20.445	20.276	21.929	21.686	20.488
Avg. ISL Delay (ms)	104.463	1054.752	4495.769	11356.011	129.578	979.190	3922.225	10474.163
Avg. # of Iterations	20.276	21.665	20.641	19.302	20.276	21.676	20.626	19.242
Avg. # of Attempts	1.000	2.076	7.254	17.598	1.000	1.914	6.392	16.188

which is highlighted due to its advantages of a high transmission rate and system miniaturization, in terms of satellite routing path discovery. Despite the fact that the optical ISL has additional latency due to the PAT process for link establishment, we conducted a performance comparison between the RF and optical systems of the packet transmission environment to verify the advantages of the extremely high bandwidth and data rates associated with optical communications. As a result, due to the additional delay during the PAT process, the optical communication performances were worse with a small number of packets, but it was confirmed that the performance was much better than that of the RF system as the number of packets increases. Therefore, we anticipate that the optical ISL approach will provide a great benefit during the development of future satellite networks.

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