

Pareto-Optimal QoS Routing in LEO Satellite Networks via Pointing-Error-Aware Link Metrics

Sungmin Hong, Sangmin Han, Seongjin Jeong, and Wonjae Shin

School of Electrical Engineering, Korea University, Seoul, South Korea

Email: {min050620, smhan22, jsj3020, wjshin}@korea.ac.kr

Abstract—Routing in low Earth orbit (LEO) satellite networks is a key enabler of 6G non-terrestrial networks, allowing long-distance data transmission through inter-satellite links (ISLs) without relying on terrestrial gateways. While QoS-aware routing has received increasing attention, existing studies largely overlook the physical constraints of laser ISLs, particularly pointing errors induced by the relative angular motion between satellites. In this paper, we propose a pointing-error-aware QoS link metric that jointly captures the ISL time delay and the optical link margin. Specifically, the link margin accounts for both ISL distance and receiver pointing error, where the latter is modeled as a function of the relative line-of-sight angular velocity using a control-theoretic tracking model. Based on the proposed link metric, Dijkstra’s algorithm is employed to determine minimum-cost routing paths across the LEO satellite network. Using Starlink two-line element (TLE) data and realistic laser terminal constraints, simulation results reveal a fundamental trade-off between routing delay and link margin. By constructing Pareto curves and applying the Kneedle algorithm, we identify destination-specific optimal weight pairs and develop a *Pareto-optimal QoS routing* framework. The results demonstrate that the proposed approach achieves a favorable balance between latency and link reliability in large-scale LEO satellite networks.

Index Terms—LEO satellite networks, QoS-aware routing, inter-satellite link, routing, link margin, Pareto optimization.

I. INTRODUCTION

Low Earth orbit (LEO) satellite networks, as a key component of non-terrestrial networks (NTNs) envisioned for 6G, provide global coverage independent of terrestrial infrastructure [1]. Inter-satellite links (ISLs) enable direct communication between satellites and are increasingly realized through laser-based free-space optics (FSO) rather than radio-frequency (RF) communication. FSO offers high bandwidth and low interference owing to its narrow beam width, which makes it well suited to space environments [2]. At the same time, narrow beam width imposes strict pointing requirements, increasing the need for pointing, acquisition, and tracking (PAT) systems that employ a gimbal for coarse pointing and a fast-steering mirror (FSM) for fine tracking. Building on these technologies, routing over satellite networks has emerged as a key research topic, as it enables long-distance data transmission from a source to a destination through intermediate satellites without relying on terrestrial gateways.

In the context of LEO satellite network routing, satisfying critical quality of service (QoS) requirements—specifically high data rate, high signal-to-noise ratio (SNR), and low bit error rate (BER)—is essential to achieve reliable satellite

communications. To address these demands, various routing approaches have been widely explored. Notably, both optimization- and learning-based approaches have been actively investigated, including software-defined network (SDN) controller placement optimization and deep reinforcement learning (DRL)-based inter-satellite routing [3], [4]. In addition to learning-based methods, a QoS-aware routing approach considering both time delay and power requirement was implemented within the snapshot-based routing framework, and its performance was analyzed under varying weight pairs [5].

However, existing studies neglect the physical constraints of real-world laser terminals, such as the maximum tracking angular velocity and the communication range. They also fail to model the pointing error with respect to the relative angular velocity between satellites, which significantly affects the link quality. Furthermore, existing end-to-end routing studies do not account for the impact of varying destination gateways on routing performance. To address these limitations, we incorporate real-world laser terminal constraints, such as the maximum tracking angular velocity and the communication range, as thresholds for link feasibility. We then propose a QoS-aware link metric that jointly accounts for the time delay and the link margin. In particular, we model the link margin as a function of both the distance and the receiver pointing error, where the latter results from the relative angular velocity and is captured via a control-theoretic formulation. Building on the proposed link metric, we apply Dijkstra’s algorithm to find the routing path from the source gateway to the destination gateway. We then demonstrate that the two routing performance metrics, total time delay and average link margin, exhibit a trade-off relationship, and identify the knee point of the corresponding Pareto curve for representative destinations via the Kneedle algorithm. Based on these results, we propose a Pareto-optimal QoS routing scheme that employs destination-adaptive weight pairs.

The remainder of this paper is organized as follows: Section II introduces the system model, Section III describes the proposed method, Section IV provides simulation results, and Section V concludes the paper.

II. SYSTEM MODEL

A. Network Model

LEO satellites form links not only with ground gateways but also with neighboring satellites via ISLs. Each satellite is typically equipped with four laser terminals: the front and back

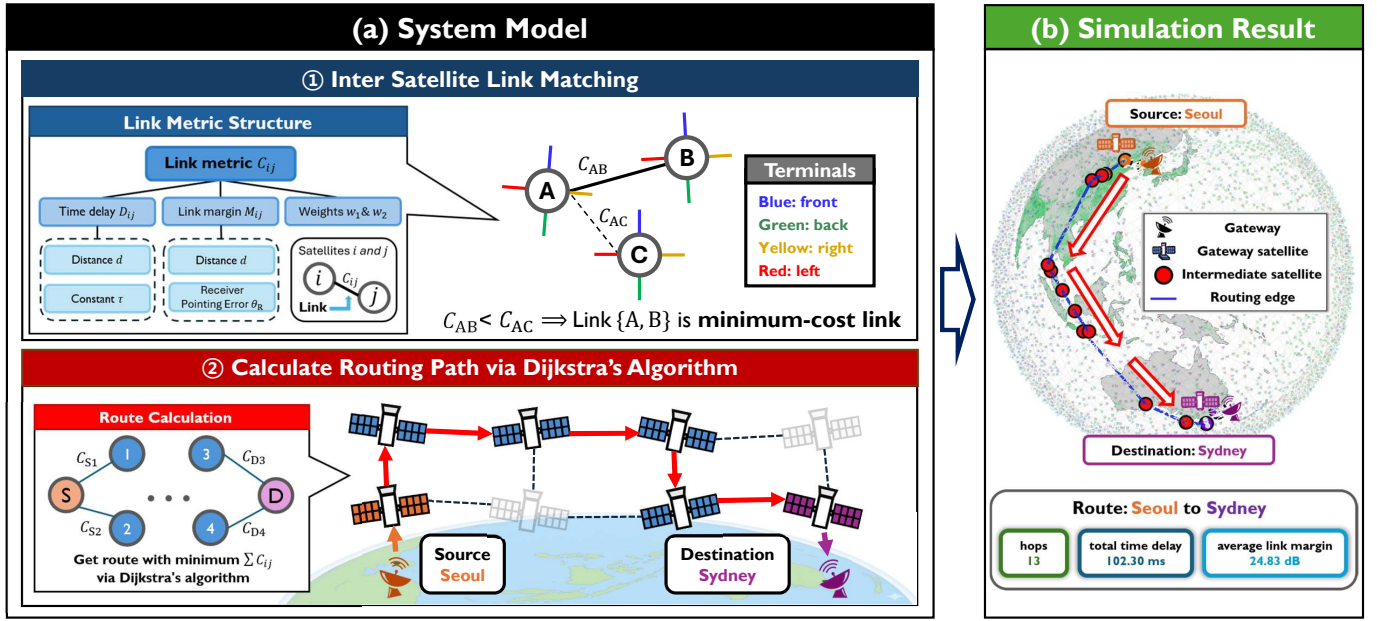


Fig. 1: Proposed QoS-aware ISL matching and routing framework: (a) system model and (b) Seoul-to-Sydney routing result.

terminals connect to adjacent satellites within the same orbital plane, while the left and right terminals connect to satellites in other orbital planes [6]. Accordingly, in this study we assume that the front and back laser terminals form permanent ISLs that are maintained throughout operation, while the left and right terminals form dynamic ISLs that can be re-established with other satellites depending on the link conditions.

B. Time Delay

The time delay between two satellites comprises two components: 1) the propagation delay, which is determined by the link distance and the speed of light; and 2) the additional delays caused by other factors such as queuing and on-board processing. Since the latter are difficult to model and not the focus of this work, we aggregate them into a single constant τ . Accordingly, the ISL time delay between satellites i and j is given by:

$$D_{ij} = \frac{d}{c} + \tau, \quad (1)$$

where d and c denote the distance between two satellites and the speed of light, respectively.

C. Link Margin

A link budget accounts for the gains and losses along the path from the transmitter to the receiver in a wireless system. In FSO links, the received power P_R is given by:

$$P_R = P_T \eta_T \eta_R G_T G_R L_T L_R L_{PS}, \quad (2)$$

where P_T and P_R are the transmitted and received powers, respectively; η_T and η_R are the transmitter and receiver optics efficiencies, respectively; G_T and G_R are the transmitter and receiver gains, respectively; L_T and L_R are the transmitter and receiver pointing losses, respectively; and L_{PS} is the free-space path loss [2]. With the exception of the constants P_T , η_T , and η_R , the remaining terms are determined by the wavelength

λ , the distance d , the transmitter and receiver pointing errors θ_T and θ_R , respectively, the receiver aperture diameter D_R , and the full transmit divergence angle Θ_T . Specifically, the gains are given by $G_T = 16/\Theta_T^2$ and $G_R = (\pi D_R/\lambda)^2$; the pointing losses are given by $L_T = \exp(-G_T \theta_T^2)$ and $L_R = \exp(-G_R \theta_R^2)$; and the free-space path loss is given by $L_{PS} = (\lambda/4\pi d)^2$. In this study, all system parameters are fixed, except for the distance d and the receiver pointing error θ_R . Link margin, which represents the excess received power over the minimum required power between two satellites i and j , is defined as:

$$M_{ij} [\text{dB}] = P_{R,ij} [\text{dBm}] - P_{\text{req}} [\text{dBm}], \quad (3)$$

where $P_{\text{req}} = -35.5 \text{ dBm}$ is the minimum received power required for a data rate of 10 Gbps at a BER of 10^{-12} under on-off keying (OOK) modulation. A non-negative link margin is required for a feasible link, whereas a margin of at least 3 dB is typically required for reliable communication. As illustrated in Fig. 2, the link margin decreases as the link distance and the receiver pointing error increase. The receiver pointing error θ_R as a function of the LoS angular rate ω is derived in Section III.

D. Link Feasibility Constraints

At each simulation frame, the feasible links between the right and left terminals are determined by applying the following constraints which reflect real-world laser terminal capabilities and link budget requirements: (1) inter-satellite distance below 3,000 km; (2) angle below 90° between the laser terminal direction and the relative position vector of the two satellites; (3) remaining visibility time at least 60 s; (4) relative line-of-sight (LoS) angular rate below 5° s^{-1} ; and (5) inter-satellite link margin of at least 3 dB [2], [7]. For the front and back terminals, feasibility is determined using a threshold angle of 20° .

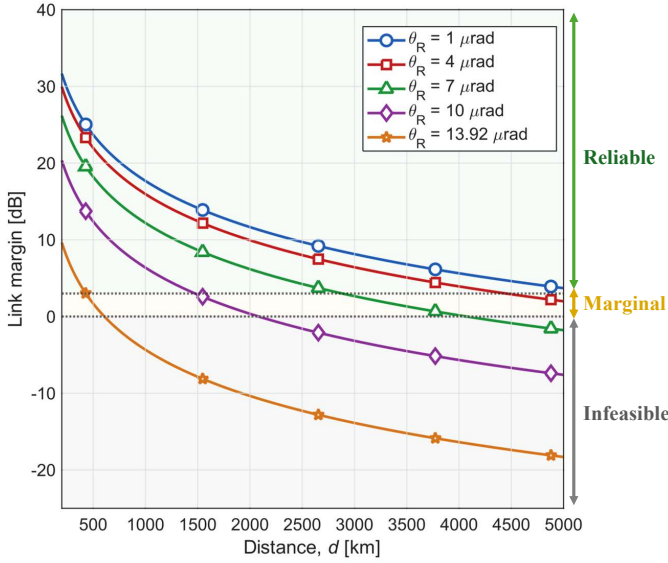


Fig. 2: Link margin versus ISL distance for various receiver pointing errors.

III. POINTING-ERROR-AWARE LINK METRIC AND PARETO-OPTIMAL ROUTING FRAMEWORK

A. Receiver Pointing Error Model

In the link budget evaluation in (2), the receiver pointing error θ_R is set to the RMS-equivalent value $\theta_R^{\text{RMS}}(\omega)$. Extending the pointing error model of [8], which characterizes the jitter and bias contributions, we add a tracking lag to account for the pointing error induced by the LoS angular rate between satellites. The total receiver pointing error is thus expressed as

$$\theta_R = \theta_{\text{lag}} + \theta_{\text{jitter}} + \theta_{\text{bias}}, \quad (4)$$

where θ_{lag} represents the pointing error caused by the tracking delay of the FSM, θ_{jitter} is the random error caused by thermal effects and internal variations, and θ_{bias} is the systematic bias error. We assume θ_{bias} to be 0, and that the jitter follows a zero-mean Gaussian distribution as follows:

$$\theta_{\text{jitter}} \sim \mathcal{N}(0, \sigma_{\text{jitter}}^2), \quad (5)$$

where σ_{jitter} is set to $1 \mu\text{rad}$ [9]. Since the jitter is zero-mean and independent of the deterministic tracking lag, the effective RMS pointing error is given by

$$\theta_R^{\text{RMS}}(\omega) \triangleq \sqrt{\mathbb{E}[\theta_R^2]} = \sqrt{\theta_{\text{lag}}^2(\omega) + \sigma_{\text{jitter}}^2}. \quad (6)$$

Using standard control-theoretic analysis, the tracking lag θ_{lag} can be modeled as a function of ω [10]. Since the LoS angle increases linearly with time as $\theta_{\text{LoS}}(t) = \omega t$, the corresponding Laplace-domain input is $R(s) = \omega/s^2$. Assuming that the FSM tracking loop behaves as a Type-1 unity-feedback control system with $G(s) \approx \omega_c/s$, the steady-state error under this ramp input is obtained via the final value theorem as

$$\theta_{\text{lag}} = \lim_{s \rightarrow 0} s \cdot \frac{1}{1 + G(s)} \cdot \frac{\omega}{s^2} \approx \frac{\omega}{K_v}, \quad (7)$$

where $G(s)$ is the transfer function and $K_v \triangleq$

$\lim_{s \rightarrow 0} sG(s) = \omega_c$ is the velocity error constant, representing the loop's ability to track a ramp input without unbounded error growth. Using $\omega_c = 2\pi f_c$, the steady-state pointing lag is expressed as

$$\theta_{\text{lag}} \approx \frac{\omega}{2\pi f_c}, \quad (8)$$

where f_c denotes the closed-loop bandwidth of the FSM tracking loop. We set f_c to 1 kHz to reflect realistic FSM tracking loop requirements [9]. As shown in (8), the pointing lag increases linearly with the LoS angular rate ω and the maximum RMS pointing error $\theta_R^{\text{RMS}}(\omega)$ is calculated to be $13.92 \mu\text{rad}$. Fig. 2 reveals that both the distance and receiver pointing error significantly affect the link margin. In particular, the maximum $\theta_R^{\text{RMS}}(\omega)$ of $13.92 \mu\text{rad}$ severely degrades the link margin, pushing it into the marginal or infeasible regions.

B. QoS-Aware Link Metric

In OOK-based FSO links, key QoS metrics, such as SNR, BER, and bit rate, can be approximately derived from the link margin [11]. We therefore adopt the time delay D_{ij} and link margin M_{ij} as the two representative QoS metrics, from which the QoS-aware link metric is defined. Since the two metrics have different scales, we apply min-max normalization to map each to the range $[0, 1]$. The normalized time delay and link margin are given as follows:

$$\hat{D}_{ij} = \frac{D_{ij} - D_{\min}}{D_{\max} - D_{\min}}, \quad (9)$$

$$\hat{M}_{ij} = \frac{\text{clip}(M_{ij}, M_{\min}, M_{\max}) - M_{\min}}{M_{\max} - M_{\min}}, \quad (10)$$

where $\text{clip}(x, a, b) = \min\{\max\{x, a\}, b\}$ bounds x to the interval $[a, b]$. Here, $D_{\max}$ and $D_{\min}$ are given by

$$D_{\max} = \frac{d_{\max}}{c} + \tau, \quad D_{\min} = 0, \quad (11)$$

where $d_{\max}$ denotes the maximum allowable ISL distance. $M_{\max}$ and $M_{\min}$ are set to 25 dB and 3 dB, respectively. Since a link margin above 25 dB is sufficient for reliable communication, the clip operator upper-bounds the margin at $M_{\max}$. The lower bound $M_{\min}$ coincides with the minimum link margin enforced as a feasibility constraint.

Consequently, the weighted link metric is defined as

$$C_{ij} = w_1 \hat{D}_{ij} + w_2 (1 - \hat{M}_{ij}), \quad (12)$$

where w_1 and w_2 denote the weights for the normalized time delay and link margin terms, respectively, subject to $w_1 + w_2 = 1$. Since a higher link margin corresponds to a lower communication cost, the normalized link margin is subtracted from 1.

For the left and right terminals, the link metric C_{ij} is evaluated for each feasible candidate ISL, and the candidate with the minimum metric is selected via a greedy algorithm, as shown in Fig. 1. In contrast, the front and back terminal links are initially established by selecting the satellites with the longest remaining visibility time, thereby approximating connections to adjacent satellites within the same orbital plane.

TABLE I: System Parameters

Parameter	Symbol	Value
Wavelength	λ	1,550 nm [2]
Transmit power	P_T	30 dBm
Transmitter optical efficiency	η_T	0.8 [2]
Receiver optical efficiency	η_R	0.8 [2]
Receiver aperture diameter	D_R	80 mm [2]
Transmit divergence angle	Θ_T	15 μ rad [2]
Receiver sensitivity	P_{req}	-35.5 dBm [2]
Transmit pointing error	θ_T	1 μ rad [2]
Processing delay	τ	5 ms [12]

C. Pareto-Optimal QoS Routing Scheme

The proposed Pareto-optimal QoS routing scheme consists of two steps: 1) QoS-aware path computation and 2) Pareto-based weight selection.

1) *QoS-aware path computation*: Once the links are established, we compute the route from the source gateway to the destination gateway as shown in Fig. 1. Each gateway is connected to a satellite that satisfies the elevation-angle threshold of 30°. When the remaining visibility time of the serving satellite drops below 60 s, the gateway hands over to the visible satellite with the highest remaining visibility time. In each frame, we construct a graph $G = (V, E)$, where V is the set of all LEO satellites, and E is the set of edges comprising the permanent and temporary links. We then apply Dijkstra's algorithm with the proposed link metric C_{ij} to obtain the routing path with the minimum total link metric.

2) *Pareto-based weight selection*: To determine the optimal weight pair (w_1, w_2) , we identify the knee point in the Pareto curve obtained from different weight configurations. Specifically, the normalized total time delay $\bar{D} \in [0, 1]$ and the normalized average link margin $\bar{M} \in [0, 1]$ are plotted on the x-axis and y-axis, respectively, across various weight pairs (w_1, w_2) , forming a discrete Pareto curve. The resulting curve reveals that improving one metric necessarily degrades the other, motivating the need for a knee point that represents the most balanced trade-off relationship between the two competing objectives. To identify the knee point of the discrete Pareto curve, we adopt the Kneedle algorithm, which locates the knee point on the normalized Pareto curve that maximizes the perpendicular distance from the diagonal reference line $y = x$ [13]. By adopting the weight pair at this point, the proposed scheme achieves Pareto-optimal QoS routing that jointly accounts for time delay and link margin.

IV. PERFORMANCE ANALYSIS AND DISCUSSION

A. Simulation Setup

Our simulator is implemented in Python, building on the open-source code of [14]. We obtain the Starlink two-line element (TLE) data from CelesTrak, retrieved at approximately 04:00 UTC on April 3, 2026. We consider 10,119 satellites contained in the dataset and their positions are propagated using the Simplified General Perturbations model 4 (SGP4) propagator. The simulation time step is 1 s. The system parameters are summarized in Table I.

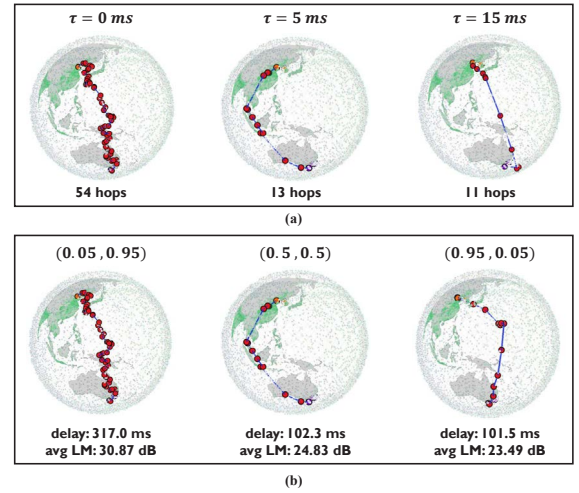


Fig. 3: Simulation results of the proposed routing algorithm for a Seoul-to-Sydney path: (a) routing paths with varying τ and (b) routing paths with varying (w_1, w_2) .

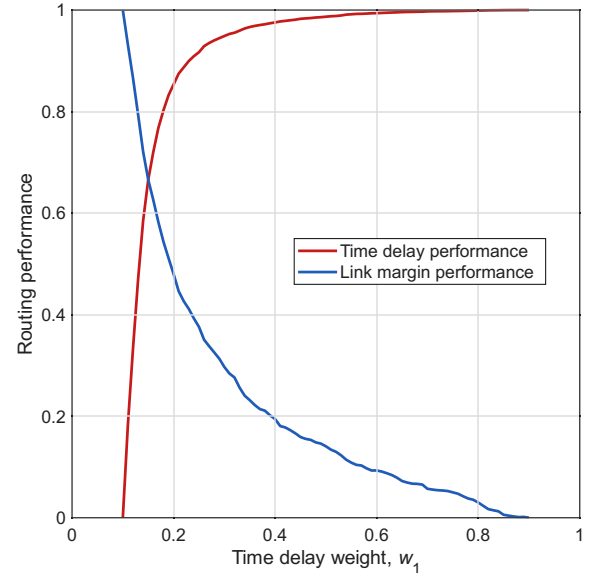


Fig. 4: Routing performance metrics versus time delay weight w_1 .

B. Simulation Results and Performance Analysis

The routing simulation results are illustrated in Fig. 3. To examine the effect of processing delay τ , simulations are conducted with varying values of τ while fixing the weight pair (w_1, w_2) to (0.5, 0.5). As shown in Fig. 3(a), a smaller τ leads to a larger number of hops, as the penalty associated with additional hops becomes relatively negligible. Fig. 3(b) compares the routing paths under varying weight pairs (w_1, w_2) with τ fixed to 5 ms, where a higher w_1 produces a lower total time delay but a smaller average link margin.

To examine the trade-off between time delay and link margin, we vary the weight pair (w_1, w_2) from (0.10, 0.90) to (0.90, 0.10) in steps of 0.01. For each pair of weights, we run the simulation for 600 s, establish the links, and calculate the Seoul-to-Sydney route in each frame. We then report the total time delay and average link margin averaged over the 600 s simulation. As shown in Fig. 4, the time delay performance is defined as $1 - \bar{D}$, where $\bar{D}$ denotes the min-max normalized

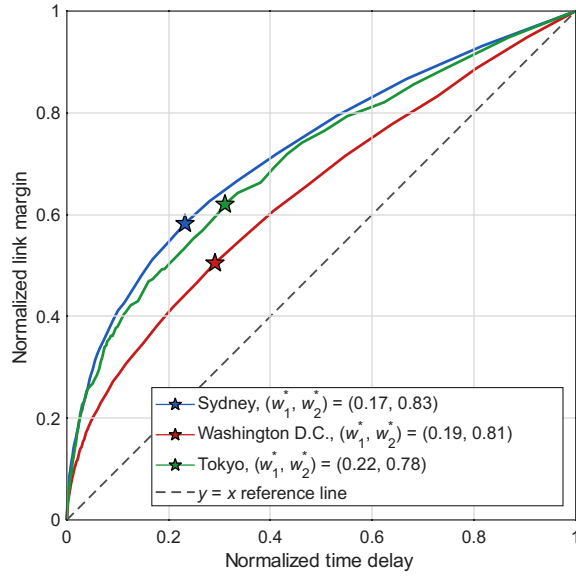


Fig. 5: Pareto curves of normalized routing performance metrics for Seoul-to-Sydney, Seoul-to-Washington D.C., and Seoul-to-Tokyo routes with knee points.

total time delay. Thus, a higher $1 - \tilde{D}$ indicates better time delay performance. The link margin performance is represented by the min-max normalized average link margin $\tilde{M}$, where a higher value of $\tilde{M}$ indicates better link margin performance. As w_1 increases, the time delay performance improves while the link margin performance decreases, demonstrating that the two routing performance metrics exhibit a trade-off relationship.

C. Optimal Weight Pair for Various Destinations

To show that the optimal weight pair varies between different destinations, we evaluate three representative destinations: Sydney, Washington D.C., and Tokyo. As shown in Fig. 5, the Pareto curve is conventionally represented using the total time delay as the cost metric on the x-axis and the average link margin as the performance metric on the y-axis. By applying the Kneedle algorithm to each curve, the optimal weight pairs are identified as $(w_1^*, w_2^*) = (0.17, 0.83)$ for Sydney, $(0.19, 0.81)$ for Washington D.C., and $(0.22, 0.78)$ for Tokyo. The destination-dependent variation in the optimal weight pairs indicates that the appropriate balance between time delay and link margin objectives should be adjusted according to the destination.

V. CONCLUSION

In this paper, we propose a QoS-aware link metric composed of time delay and link margin. Based on the constructed satellite network topology, Dijkstra's algorithm is applied to determine the routing path with minimum total link metric. Through simulations using more than 10,000 Starlink satellites, we show that the two routing performance metrics, total time delay and average link margin, exhibit a clear trade-off relationship. Furthermore, by evaluating three representative destination gateways—Sydney, Washington D.C., and Tokyo—and plotting their Pareto curves, we observe that the knee points

differ across destinations. These results indicate that Pareto-optimal QoS routing, which enables adaptive weight tuning according to destination, is effective in achieving balanced routing performance in LEO satellite networks.

ACKNOWLEDGMENT

This work was supported by the IITP (Institute of Information & Communications Technology Planning & Evaluation)-ITRC (Information Technology Research Center) grant funded by the Korean government (Ministry of Science and ICT) (IITP-2026-RS-2024-00436887).

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