

Energy-Efficient Routing via Path Aggregation and Load-Balanced Scheduling in LEO Optical Satellite Networks

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ABSTRACT The development of Optical Satellite Networks (OSNs) is crucial for the evolution of next-generation networks. A significant technical challenge that occurred in OSNs is the limited energy available of satellites, which restricts power-intensive tasks like continuous communication and link reliability. To relieve this limitation, Low-Earth-Orbit (LEO) OSNs are designed to dynamically activate and deactivate Optical Inter-Satellite Links (OISLs) based on service requests, thereby reducing continuous energy consumption from maintaining idle links. However, under heavy traffic loads, frequent on-demand OISL activation will lead to cumulative energy consumption. This problem of jointly minimizing OISL activation energy and transmission energy has not been investigated in previous studies. This study considers the energy consumption of dynamic OISL activation in OSNs. We formulated an Integer Linear Programming (ILP) model aimed at minimizing total energy consumption (including OISLs activation and transmission energy) and the number of occupied time slots, considering constraints related to the minimum residual energy threshold reserved for communication, bandwidth capacity, and time slot continuity. Then, we designed two algorithms: a Path Aggregation-based Energy Saving Algorithm (PA-ESA) algorithm, which aggregates service delivery to decrease the times of OISL activation, and an Energy-Balanced Energy Saving Algorithm (EB-ESA) algorithm, which aims to balance energy usage across satellites with less energy costs. Through extensive simulations conducted on a traditional Walker-Delta constellation generated in the Satellite Tool Kit simulator under varying traffic loads, we compared the proposed algorithms with several baseline algorithms, and the results show the effectiveness of the proposed algorithms.

INDEX TERMS Optical satellite networks, energy management, routing and resource allocation.

I. INTRODUCTION

With the escalating global demand for seamless information exchange, it is essential to facilitate information exchange among users worldwide. Although terrestrial networks (e.g., F6G) are evolving rapidly, their cost-effectiveness is primarily confined to densely populated areas [1-3]. Conversely, providing coverage to remote regions, such as maritime and mountainous terrains, necessitates the integration of non-terrestrial communication infrastructures [4, 5]. Consequently, non-terrestrial networks have emerged as a focal point of both academic and industrial research [6-8].

Among various non-terrestrial networks, Optical Satellite Networks (OSNs) are pivotal for achieving global broadband connectivity [9, 10]. By leveraging free-space optical

communications, OSNs enable Optical Inter-Satellite Links (OISLs) that offer significant advantages over traditional radio-frequency systems, including broader bandwidth, enhanced security, and superior immunity to physical interference [11-13]. In particular, establishing OISLs between Low-Earth-Orbit (LEO) satellites can further improve communication performance by reducing propagation delays due to their relatively low orbital altitudes [14]. To exploit these benefits, commercial LEO mega-constellations, such as Starlink [15] and Telesat Lightspeed [16], have deployed onboard laser communication terminals.

With the rapid deployment of LEO mega-constellations, the number of feasible OISLs in OSNs has increased exponentially. Due to the high density of the constellations, a single satellite has a vast number of other spacecraft within

its line-of-sight at any given instant. Although a satellite typically carries only four laser communication terminals for persistent intra-orbit and inter-orbit links, the spatial geometry allows it to observe dozens of potential candidates across different orbital layers. Through dynamic beam steering, each satellite can maintain a pool of tens of potential link targets. This abundance of line-of-sight opportunities offers great flexibility for network routing. However, establishing and maintaining all feasible OISLs in a continuously active state incurs physical limitations and substantial management overhead of network operation, which represents an inefficient allocation of network resources. Furthermore, traffic demands in practical OSNs are geographically uneven, predominantly concentrating over densely populated and economically active regions. Consequently, OSNs have a hybrid topology comprising both active and inactive OISLs. Regarding this, recent studies gradually move from traditional always-on link configurations toward on-demand OISL establishment, such as the designed demand-driven topologies [17-19].

To improve network efficiency, selective OISL activation is increasingly adopted. When a service request arrives, the routing algorithm can determine not only the forwarding path but also whether additional inactive OISLs need to be activated to accommodate the services. Unlike microwave communication for satellites, the establishment and maintenance of OISLs rely on fine-grained Acquisition, Tracking, and Pointing (ATP) procedures, which are not instantaneous and require a non-negligible setup duration ranging from a few seconds to tens of seconds [20]. Consequently, each newly activated OISL incurs an additional energy cost for link establishment beyond the continuous transmission energy. Crucially, over densely populated user regions, the dynamic arrival of abundant service requests will frequently trigger multi-hop path setups. OISLs may be frequently switched on and off, resulting in repeated ATP activation that generates substantial cumulative establishment overhead. From the network perspective, this accumulated activation energy not only strains the limited power supply of satellites over the long term but also constitutes a non-negligible component of the overall network energy consumption. Therefore, routing algorithms and OISL activation states are inherently coupled and should be jointly considered in energy-efficient routing optimization in OSNs.

Most existing energy-aware routing studies in LEO satellite networks generally assume that satellite links are considered connected as long as they are geometrically visible. The satellite connectivity was abstracted to network topology by using visibility-driven topology or snapshots at various time points. Among energy-aware routing studies, the primary focus remains strictly on transmission-related energy optimization (e.g., path length or bandwidth utilization) under the assumption of permanently active links [21-23]. Because practical optical ISLs are not continuously active, traditional routing algorithms may inadvertently

trigger additional OISL activation, leading to energy inefficiency. Consequently, energy-efficient routing strategies in OSNs not only affect transmission energy consumption but also determine whether additional OISL activation can be triggered.

Motivated by the aforementioned background and problem, path aggregation provides an effective approach by encouraging multiple service requests to share already active OISLs to save energy. Our objective is to increase path overlap among numerous services in the network layer. The number of newly activated OISLs can be reduced, thereby decreasing the activation frequency of ATP and the associated energy expenditure. The contributions of the paper are summarized as follows.

- To optimize this energy consumption for green satellite networking, the energy-efficient Path Aggregation (PA) optimization problem is formulated under a comprehensive set of constraints, including activation, link, wavelength, and bandwidth constraints.
- Given the high computational complexity of the formulated ILP, we designed two novel indices, i.e., the Link Activation Reuse Index (LARI) and the Activation-Transmission Trade-off Index (ATTI). Specifically, LARI quantifies the degree of path sharing, while ATTI evaluates the ratio of link-activation energy savings to the additional energy costs incurred during transmission.
- Leveraging these two indices, we proposed two heuristic algorithms, i.e., a Path Aggregation-based Energy Saving Algorithm (PA-ESA) and an Energy-Balanced Energy Saving Algorithm (EB-ESA). To reduce the energy costs for link activation, the PA-ESA can aggregate service paths over the reused links. To mitigate uneven energy consumption across satellites, the EB-ESA aims to improve energy balancing among satellites and avoid excessive energy consumption of heavily loaded satellites.
- Finally, extensive simulations were conducted under varying traffic loads using a series of snapshot topologies. The PA-ESA can reduce the mean energy consumption and average hop count by up to 2.92% and 0.282 hops, respectively, incurring only a minor 0.44% increase in blocking probability. Meanwhile, EB-ESA achieves an energy reduction of up to 7.51% and decreases the average hop count by 0.62 hops, while successfully balancing network energy overhead at a cost of a 0.65% maximum increase in blocking probability.

The remainder of the paper is structured as follows: **Section II** provides the background of OSNs, discussing the energy consumption of OISLs, as well as current energy-efficient routing methods. **Section III** introduces the network model, service model, and problem formulation. In **Section IV**, the PA-ESA and EB-ESA algorithms are introduced. **Section V** presents illustrative numerical results, and **Section VI** concludes the paper.

II. BACKGROUND

A. OSNs

OSNs generally comprise ground and space segments, as illustrated in Figure 1. The ground segment mainly consists of gateways, user terminals, and terrestrial networks, which are responsible for traffic access, control, and service delivery. The space segment consists of LEO satellites interconnected through OISLs, forwarding traffic over long distances. To increase communication capacity, OISLs can be further divided by Wavelength Division Multiplexing (WDM) techniques [24, 25], allowing multiple wavelengths to be transmitted simultaneously over a single optical link. To connect space and ground segments, uplink and downlink can be established via microwave communication for traffic upload and download. This study focuses on the OISLs achieved by WDM in the space segment.

According to the relative orbital geometry, OISLs can be established between satellites in the same orbital planes and crossing orbital planes. Satellites in the same orbital planes move with nearly identical velocities and maintain almost constant relative positions, whose OISLs have long visibility windows. While satellites in the crossing orbital planes have varying positions and angular velocities, whose distance variation is within a limited range during their temporal visibility windows (which is about 283 s duration in a Starlink Phase I constellation geometry and 550 km orbital altitude [26]). The OISLs are repeatedly established and disconnected as satellites move along their orbits, resulting in frequent ATP processes throughout network operation. In practical cases, the above physical information, like distance and visibility window, can be estimated within a limited range for on-demand OISL establishment.

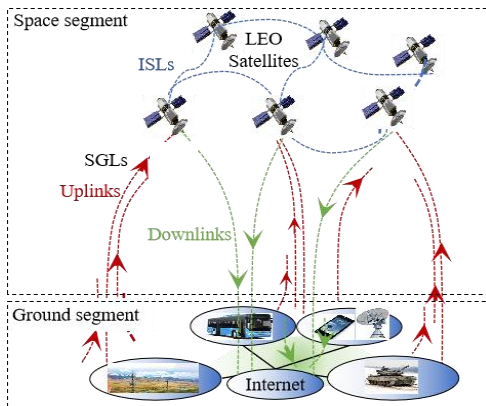


FIGURE 1. The illustration of an OSN.

B. ATP FOR LASER COMMUNICATION IN SATELLITES

ATP plays a critical role in establishing and maintaining OISLs. A typical ATP system for a LEO satellite's laser terminal consists of a Coarse Pointing Assembly (CPA) and a Fine Pointing Assembly (FPA). The CPA provides coarse alignment of laser beams and has a wide field of view and low precision. The FPA has a narrow field of view and high precision and aligns laser beams to achieve the desired pointing accuracy. The CPA can enable the ATP system to

achieve rough pointing in the desired direction by rotating the laser terminal via the control system without reorientation of the body pointing of the satellite. The ATP system of some small satellites, like CubeSats designed in the CubeSat Lasercom Infrared Crosslink (CLICK) project [27], does not use a CPA and relies on the satellite's altitude determination and control system for body pointing to achieve coarse pointing. Differently, the ATP system in SpaceX's Starlink satellites needs a CPA for the satellite to establish OISLs with different neighbors in different directions simultaneously, and body pointing (or satellite reorientation) to reduce energy consumption is not feasible for Starlink-like LEO satellites.

The energy efficiency of the ATP system of satellites can be improved from both hardware and network-layer perspectives. From the hardware perspective, designing the ATP system for OISLs entails a stringent trade-off between minimizing Size, Weight and Power (SWaP) to maintain the desired tracking accuracy. Driven by the rigorous resource and budget constraints of satellite platforms, reducing architectural complexity becomes imperative to meet these baseline constraints. However, compressing the quality and quantity of hardware components inherently degrades system accuracy [28]. Therefore, a sophisticated ATP system is always required in practical cases, which means a higher SWaP. From the network-layer perspective, literature reviews indicate that the power of CPA can be about 5 W [29], 9.5 W [30], or 48 W [31], and the power of FPA can be about 1.56 W [31], 2 W [32], or 2.5 W [29]. Although the power of the CPA and FPA is moderate, each time of initial activation of the ATP system can last from several to tens of seconds. In large-scale LEO constellations, numerous traffic requests continuously trigger and maintain OISL establishments along routing paths. As a result, these ATP operations are executed repeatedly over LEO satellites' 4.5-to-5-year lifespan [33], leading to non-negligible cumulative energy consumption. Since this energy overhead is directly coupled with the frequency of OISL establishments, network-layer routing strategies capable of reducing redundant link activations offer an effective approach to mitigating ATP-related energy consumption.

C. ATP ENERGY CONSUMED FOR OISL

Energy consumption is important in OSNs. Satellites generally rely on solar panels [34] and rechargeable batteries

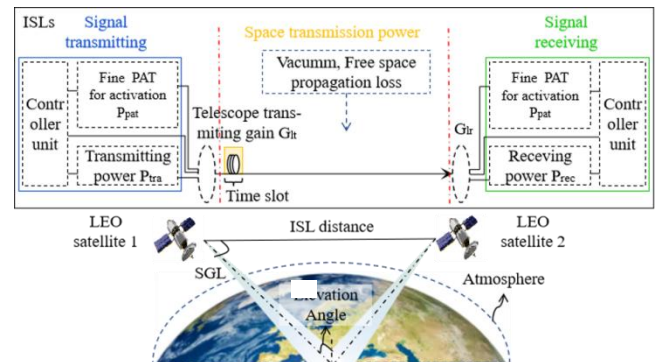


FIGURE 2. Illustration of the energy consumption of an OISL.

TABLE 1. Comparison with existing works.

Ref.	Dynamic link activation	ATP Activation Energy costs	Transmission energy costs	Energy-efficient routing	Energy-balancing routing	Jointly minimize transmission & ATP activation energy
[38]	X	X	√	√	X	X
[39]	X	X	√	X	√	X
[40]	X	X	√	√	X	X
[41]	√	X	X	√	X	X
[42]	X	X	√	√	√	X
[43]	X	X	√	√	√	X
[44]	√	X	√	X	√	X
[45]	X	X	√	√	X	X
Our work	√	√	√	√	√	√

[35] as energy sources, with limited energy storage for usage. Before establishing an OISL, satellites estimate the relative position and line-of-sight direction of the target satellite using onboard orbital ephemeris and historical altitude data. Consequently, the CPA can directly rotate toward the predicted direction instead of performing blind beam searching, while the FPA takes time to complete the subsequent fine acquisition and tracking process. During these processes, the variations of CPA and FPA are generally confined within limited physical (e.g., angle and distance) ranges for an OISL within its limited time window, owing to the identical laser terminals and regular orbital geometries of the constellation. Compounded with the moderate power consumption for the ATP summarized in Ref. [36], the variations of ATP energy cost required for OISL establishment within such bounded adjustment ranges and short acquisition windows can be reasonably approximated by average values for network-layer analysis. Combined with the widely adopted snapshot in satellite networking literature [9, 11, 18], we discretized the continuous orbital operation into multiple discrete time slots of duration. Within each short slot, the relative spatial topology, link distances, and tracking angular velocities are assumed to be fixed, represented by their average values during that interval.

Based on the above, this paper mainly considers two components of energy costs of ATP, i.e., ATP activation and maintaining, for the simplicity of network-layer abstraction. They can be denoted as, i.e., $E_{total} = E_{lact} + E_{tx}$, where E_{lact} refers to the activation energy of ATP, E_{tx} is transmission energy of ATP. Among these, since E_{lact} typically operates within a power range lasting for several seconds every time and may occur multiple times, it can be regarded as a fixed constant for each time of OISL establishment, i.e., $E_{lact} = \bar{E}_{lact}$. Once an OISL is activated, data transmission consumes energy according to the free-space optical link budget, specifically, $P_{lt} = P_{lr} - G_t - G_r + L_s + L_m$ [37]. The budget considers the gains of both transmitting and receiving telescope G_t and G_r (in dB), free-space loss $L_s = (\lambda/4\pi R)^2 \cdot e^{-\alpha R}$ (in dB), and other losses L_m (in dB), where the budget is influenced by the laser wavelength λ , link distance R , and atmospheric attenuation coefficient α . Due to the link activation based on a snapshot at a time point, we selected these parameters, which can be seen as fixed values. In this case, the energy

cost is reduced to a simple per-slot constant, which is averaged by slot duration. Accordingly, the overall energy cost can be modeled as $E_{total} = \bar{E}_{lact} + P_t \cdot t_{tr}$, which is linear in the number of active slots.

D. ENERGY-EFFICIENT ALGORITHMS IN SATELLITE NETWORKS

Unlike traditional terrestrial networks, LEO OSNs are highly dynamic, characterized by frequent fluctuations of the visibility window of OISLs. Existing energy-efficient routing algorithms focus on the problems of improving the lifespan of satellite battery and minimizing transmission energy, assuming satellites and OISLs exist physically. In contrast, OSNs should also account for the energy required to activate satellites or OISLs, which is non-negligible for the transmission.

Energy optimization in satellite networks has garnered significant research interest. For instance, Zhu et al. developed an energy-efficient resource allocation strategy for cloud-integrated terrestrial-satellite networks [38]. Liu et al. designed an intelligent energy-aware protocol to ensure delay bounds in mega constellations [39]. To minimize consumption in delay-sensitive applications, Yu et al. [40] introduced a specialized broadcasting method. In terms of protocol-layer optimization, Okonor et al. [41] established a link-cost model for OSPF to balance energy conservation with link utilization. Furthermore, several studies have focused on hardware longevity. Yang et al. [42] formulated the Green SR-A/B algorithm based on satellite recharge cycles, and Macambira et al. [43] designed routing algorithms specifically to prolong battery endurance. Liu et al. [44] proposed an inter-satellite link planning scheme using numerical quantization to balance battery lifetime and network throughput. Furthermore, Liu et al. [45] extended the green networking design to IP-over-WDM OSNs by developing energy-efficient traffic grooming strategies.

Despite these advancements, most prior works assume environments where link activation energy is negligible. In LEO OSNs, however, the energy consumed by high-precision ATP processes for OISL establishment takes time, particularly for short-duration data transmissions. Consequently, the energy-efficient routing algorithm that considers both activation and transmission costs is essential for a comprehensive evaluation of energy efficiency. As a

summary, [Table 1](#) compares our work with existing energy-efficient schemes in satellite networks.

E. Compatibility with Other Energy-Efficient Methods

To further position our work within the scope of green satellite networking, the proposed path aggregation framework is a compatible solution. It can be used in combination with other existing energy-saving hardware and network-layer methods to achieve collective energy reduction.

i) *Combination with Hardware*: While the developed algorithms (i.e., PA-ESA and EB-ESA) optimize the strategies of on/off OISL to minimize activation power, hardware-level techniques, such as dynamic voltage and frequency scaling (DVFS) [46], can be locally applied to the remaining active transceivers. Guided by the proposed LARI and ATTI metrics in [Section IV. A](#), the transmission path of traffic can be consolidated. This enables DVFS to dynamically tune the clock frequency or operational voltage of active optical modems down to the minimum threshold required to support the specific aggregated traffic volume, thereby squeezing out additional hardware-level energy savings.

ii) *Combination with Network Layer*: Standard topology-based link sleeping protocols often struggle with dynamic traffic burstiness, leading to frequent and energy-costly state-toggling. The proposed path aggregation can act as an upper-layer traffic-shaping mechanism that funnels sparse flows onto a minimal set of backbone paths. This proactive consolidation vacates underutilized OISLs and extends their

TABLE 2. Parameters definition of symbol.

Symbol	Definition
Sets:	
$G(V, L)$	Network graph.
V	Set of satellite nodes v .
L	Set of optical OISLs l .
Λ	Set of wavelengths λ .
T	Set of time slots t .
R	Set of requests r .
Parameters:	
$k(s_k, d_k, b_k, c_k)$	A request with volume c_k originates from source s_k and is destined to d_k with bandwidth requirement b_k , $k \in R$.
Δt	Time slot duration.
t_k	Holding duration of request.
E_l^{act}	Constant, activation energy for an OISL.
P_{ij}^{tx}	Constant, transmission power of OISL.
P_{ij}^{hold}	Constant, holding power of OISL.
E_{TOTAL}	Constant, total energy consumption.
Variables:	
$x_{ij}^{k,t,\lambda}$	Binary, routing variable.
$y_{ij}^{t,\lambda}$	Binary, wavelength whether available in l_{ij} .
z_{ij}^t	Binary, link activation variable.
n_{ij}^t	Binary, used to identify newly activated OISLs.
C_{ij}	Binary, link capacity.
F_{ij}^t	Binary, the number of requests sharing l_{ij} .
PA	Path aggregation metric.
α	Energy weight.
β	Aggregation weight.

idle duration, thereby creating prolonged, stable windows for underlying protocols to transition transceivers into deep sleep modes without compromising service continuity.

III. NETWORK MODEL AND PROBLEM FORMULATION

This section presents the service model, network model, decision variables, energy consumption model, and path aggregation model. Based on these models, the path aggregation optimization problem is formulated as a static ILP model. Specifically, a given set of service requests is jointly considered within the optimization horizon, and the routing, wavelength assignment, and OISL activation decisions are optimized simultaneously. The ILP formulation serves as a benchmark for evaluating the energy efficiency of the proposed heuristic algorithms under the same service and network conditions. The main symbols used in this section are summarized in [Table 2](#).

A. SERVICE MODEL

Suppose that a set of service requests R is given in advance for the considered optimization horizon. The complete request set is assumed to be known in the static ILP formulation. Each service request $k(s_k, d_k, b_k, c_k) \in R$ is characterized by the following parameters. s_k is the source satellite of the service request k . d_k is the destination satellite of the service request. b_k is the bandwidth required by the request. c_k is the total size of the request, where $0 \leq c_k$. t_k denotes the transmission duration of request k , measured in the required number of time slots $t_k = \lceil c_k / b_k \rceil$. Accordingly, a request occupies network resources only during its corresponding service period, which is represented by the associated time slot indices in the ILP.

B. NETWORK MODEL

The considered OSN is represented as topology snapshots represented by a graph $G(V, L)$, where V is the set of satellites. L comprises the set of possible OISLs. In each possible OISL, W denotes the number of wavelengths with C_{ij} wavelength capacity. Time is discretized into a set of equal-length time slots $T = \{t_1, t_2, \dots, |T|\}$ with duration Δt . For the static ILP formulation, the service requests are jointly scheduled over the considered time slots. Within each time slot, the network topology and the path selection consisting of OISLs can be assumed to remain unchanged. We assume that the time slot required by the request t_r is an integer multiple of Δt . The network topology is represented by a sequence of topology snapshots. During a single time slot, the visibility of OISLs and routing decisions are assumed to remain unchanged.

C. ROUTING DECISION VARIABLES

At the network layer, an activation of OISL is represented by a binary variable. Once an OISL is selected, the coordinated activation of its two endpoint optical terminals is assumed to be successfully completed. The ATP coordination procedure is abstracted, while its associated

activation time and power can be considered as energy consumption. To jointly determine routing, wavelength assignment, and OISL activation, the following binary variables are introduced.

i) *Routing variable*:

$$x_{ij}^{k,t,\lambda} = \begin{cases} 1, & \text{if request } k \text{ uses } l_{ij} \text{ on wavelength } \lambda \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

ii) *Wavelength variable*:

$$y_{ij}^{t,\lambda} = \begin{cases} 1, & \text{if wavelength } \lambda \text{ on } l_{ij} \text{ is available} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

iii) *OISL activation variable*:

$$z_{ij}^t = \begin{cases} 1, & \text{if } l_{ij} \text{ is activated} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

iv) *New activation variable*:

$$n_{ij}^t = \begin{cases} 1, & \text{if } z_{ij}^t = 1 \text{ and } z_{ij}^{t-1} = 0 \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

D. ENERGY CONSUMPTION MODEL

The total network energy consumption consists of three components: OISL activation energy, OISL holding energy, and transmission energy. In this work, the energy consumption associated with an active OISL is modeled at the link level to capture the energy consumption induced by path selection of service requests. Specifically, the holding power and transmission power are both modeled as link-level power consumption, which is incurred over multiple time slots of duration Δt whenever the OISL is active. This abstraction avoids introducing additional physical-layer link-budget and terminal parameters that are beyond the scope of this work.

i) *OISL activation energy*: Activation energy of ATP is consumed when a previously inactive OISL becomes active. E_{ij}^{act} denotes the activation energy of OISL l_{ij} , measured in Joules (J).

$$E_{ACT} = \sum_{t \in T} \sum_{l_{ij} \in L} E_{ij}^{act} \cdot n_{ij}^t \quad (5)$$

ii) *Holding energy of an active OISL*: Activated OISLs consume ATP maintenance power, where P_{ij}^{hold} denotes the ATP holding power of OISL, measured in watts (W).

$$E_{HOLD} = \sum_{t \in T} \sum_{l_{ij} \in L} P_{ij}^{hold} \cdot \Delta t \cdot z_{ij}^t \quad (6)$$

iii) *OISL transmission energy*: The transmission energy consumed by active OISLs is denoted as Eq. (7), where P_{ij}^{tx} denotes the transmission power, measured in W.

$$E_{TX} = \sum_{t \in T} \sum_{l_{ij} \in L} P_{ij}^{tx} \cdot \Delta t \cdot z_{ij}^t \quad (7)$$

iv) *Total energy consumption for a service*: The overall network energy consumption is given by,

$$E_{TOTAL} = E_{ACT} + E_{HOLD} + E_{TX} \quad (8)$$

E. PATH AGGREGATION MODEL

The objective of path aggregation is to encourage multiple service requests to reuse already activated OISLs. The number of requests sharing OISL l_{ij} at time slot t is defined as,

$$F_{ij}^t = \sum_{k \in R} \sum_{\lambda \in \Lambda} x_{ij}^{k,t,\lambda} \quad (9)$$

The path aggregation gain is defined as,

$$PA = \sum_{t \in T} \sum_{l_{ij} \in L} (F_{ij}^t - z_{ij}^t) \quad (10)$$

Here is an example for the path aggregation. If one service transmission uses a link, such as F_{ij}^t and z_{ij}^t , we can calculate $F_{ij}^t - z_{ij}^t = 1 - 1 = 0$, which means no aggregation gain. If three service transmissions share one activated OISL, we can calculate $F_{ij}^t - z_{ij}^t = 3 - 1 = 2$, which means aggregation gain exists. Thus, we use PA to measure the amount of traffic sharing on activated OISLs.

F. PROBLEM FORMULATION

In this study, the PA optimization problem is formulated as follows. **Given** the network graph $G(V, L)$, a set of service request $k(s_k, d_k, b_k, c_k)$, and energy-related parameters (E_{ij}^{act} , P_{ij}^{hold} , P_{ij}^{tx}), the competitive optimization **objective** (i.e., $\text{Min } \alpha \cdot E_{TOTAL} - \beta \cdot PA$) is to optimize the following twofold over an energy-effective path aggregation scheduling: The first item of the E_{TOTAL} aims to minimize total network energy consumption by jointly considering OISL activation energy, maintenance energy, and transmission energy. The second item PA maximizes the path aggregation gain, which quantifies the degree to which multiple requests reuse already activated OISLs. The weighting parameters (α) and (β) allow balancing energy minimization and path aggregation. The objective is subject to the same set of constraints (i.e., $C_1 - C_5$).

Objective:

$$\text{Min } \alpha \cdot E_{TOTAL} - \beta \cdot PA \quad (11)$$

s.t.

$$C_1 : \sum_{\{j|(ij) \in L\}} x_{ij}^{k,t,\lambda} - \sum_{\{j|(ji) \in L\}} x_{ji}^{k,t,\lambda} = \begin{cases} 1 & i = s_k \\ -1 & i = d_k \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

$$\forall k \in R, t \in T, \lambda \in \Lambda, i \in V$$

C_1 is flow conservation constraint, ensuring that for any request k at time slot t using wavelength λ , the total incoming traffic at any satellite node i must equal the total outgoing traffic.

$$C_2 : \sum_k b_k \cdot x_{ij}^{k,t,\lambda} \leq C_{ij} \quad (13)$$

C_2 is link capacity constraint, by summing up b_k of all requests passing through the l_{ij} at t on λ , and guaranteeing that the total volume does not exceed the maximum

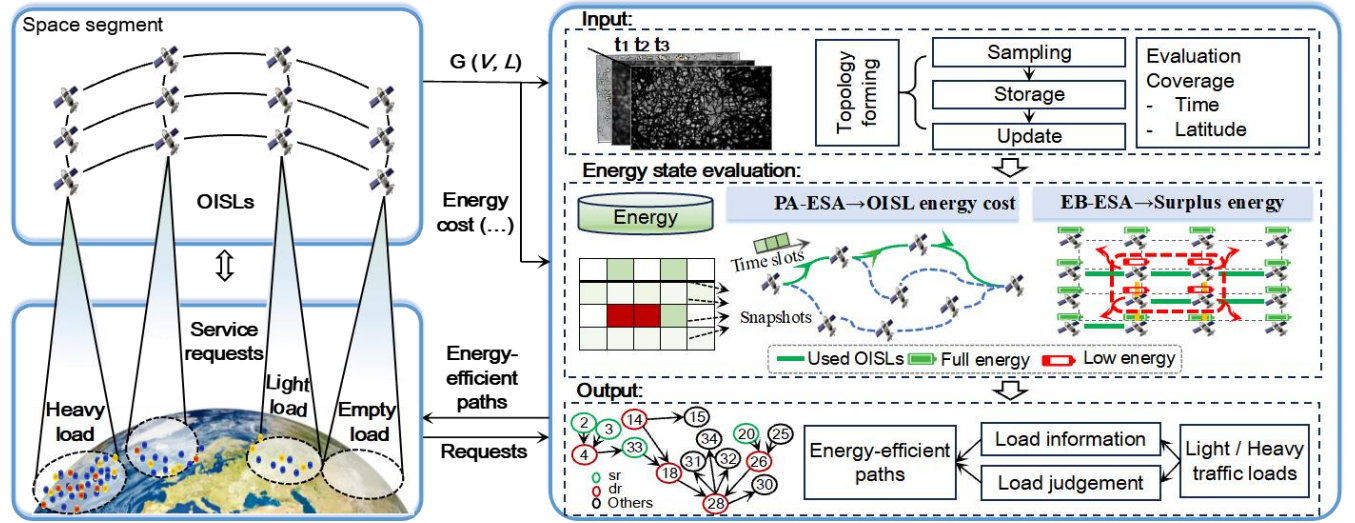


FIGURE 3. Schematic of the proposed energy-efficient algorithms.

capacity.

$$C_3: \sum_k x_{ij}^{k,t,\lambda} \leq 1, \quad \forall ij \in L, t \in T, \lambda \in \Lambda \quad (14)$$

C_3 is wavelength exclusivity constraint, ensuring that the total number of assigned services cannot exceed 1 on a specific l_{ij} at t on λ .

$$C_4: x_{ij}^{k,t,\lambda} \leq y_{ij}^{t,\lambda} \quad (15)$$

$$y_{ij}^{t,\lambda} \leq z_{ij}^t \quad (16)$$

C_4 is activation constraint. Eq.(15) ensures that a service request can be routed through l_{ij} on wavelength λ when the corresponding wavelength is enabled. Eq.(16) ensures that a wavelength can be enabled only when the corresponding OISL is activated.

$$C_5: n_{ij}^t \geq z_{ij}^t - z_{ij}^{t-1} \quad (17)$$

$$n_{ij}^t \leq z_{ij}^t \quad (18)$$

$$n_{ij}^t \leq 1 - z_{ij}^{t-1} \quad (19)$$

C_5 is time slot recording constraint. $n_{ij}^t \geq z_{ij}^t - z_{ij}^{t-1}$ means that if the link was off in the last time slot ($z_{ij}^{t-1} = 0$) but is turned on in the current time slot ($z_{ij}^t = 1$), this equation forces the action variable $n_{ij}^t = 1$. This triggers the E_{ACT} . $n_{ij}^t \leq z_{ij}^t$ and $n_{ij}^t \leq 1 - z_{ij}^{t-1}$ make sure that if the link was already open in the last time slot ($z_{ij}^{t-1} = 1$ to $z_{ij}^t = 1$), or if the link is remaining closed, n_{ij}^t stays 0.

Since the service requests and their corresponding time slot requirements are given, the ILP jointly determines the routing and resource allocation of the given requests. For each request, the routing and resource-allocation variables are defined over its corresponding time slots. Therefore, the flow-conservation, link-capacity, and wavelength-exclusivity constraints enforce the required resources during the request's period, while the corresponding allocation variables are zero outside this period.

The formulated optimization problem is an ILP problem with binary decision variables $x_{ij}^{k,t,\lambda}$, which jointly couples routing, resource allocation, and link activation decisions. The problem has time complexity $O(|R| \cdot |T| \cdot |L| \cdot |A|)$ where $|L| \approx |V|^2$ in dense satellite graphs. In scenarios of tens of nodes and requests, the ILP can be solved using commercial solvers, but the computational time increases exponentially with the number of requests and candidate paths. The overall problem size increases rapidly with constellation scale, making exact solutions computationally intractable for large-scale networks.

IV. ENERGY-EFFICIENT HEURISTIC ALGORITHM

Unlike the static ILP formulation in Section III, the proposed heuristic algorithms process service requests dynamically as they arrive over time. Therefore, the state of an established OISL may be maintained across request arrivals to facilitate subsequent path reuse and avoid repeated ATP activation. This section introduces the concept of link activation energy reuse and presents two heuristic algorithms to reduce energy consumption in OSNs, i.e., PA-ESA and EB-ESA. The schematic of our proposed energy-efficient algorithms is shown in Figure 3.

A. Link Activation Energy Reuse Across Multiple Services

In OSNs, activating an OISL incurs non-negligible additional energy consumption. However, if multiple services traverse the same OISL, this activation cost can be amortized across them, effectively reducing the total activation energy. This motivates the aggregation of service paths to maximize the reuse of already-activated OISLs.

To formalize this, we introduce two key metrics, i.e., Link Activation Reuse Index (LARI) and Activation-Transmission Trade-off Index (ATTI). LARI quantifies the degree of overlapped link utilization. ATTI evaluates the network energy efficiency of aggregated paths by weighing the saved activation energy against the additional transmission energy caused by potential detours. Since both

LARI and ATTI are normalized by the link numbers of the path, they reflect the effect of the end-to-end hop count on the link-reuse ratio and the corresponding activation-energy benefit.

i) **Definition 1:** LARI is defined as the ratio between the reused times u_l of an already activated OISL l and the total link numbers u_l without the re-utilization, as shown in Eq. (20). If $LARI \rightarrow 1$ for a path, a large proportion of OISL usages correspond to reuse of already activated OISLs, indicating a high degree of path sharing. Conversely, if $LARI \rightarrow 0$, most OISL usages correspond to their first use, indicating limited reuse and potentially higher cumulative activation costs.

$$LARI = \frac{\sum_{l \in P} (u_l - 1)}{\sum_{l \in P} u_l} \quad (20)$$

ii) **Definition 2:** ATTI is defined as the ratio between the total saved activation energy and the excess transmission energy caused by path detours introduced during the aggregation, as shown in Eq. (21). Let ΔE_{lact}^{saved} denote the saved activation energy. The denominator is the excess energy costs introduced by path detours. If aggregating $u_l - 1$ ISLs in a path, the aggregated path may cause extra $p \cdot \bar{E}_{lact} + q \cdot P_t \cdot t_{tr}$ energy costs by path detour. Let p denote the number of link activations saved due to the aggregation, and q denote the number of additional links introduced by the aggregation. An $ATTI > 1$ indicates that the saved activation energy outweighs the detour-induced transmission cost, making the aggregated path energy-efficient. Conversely, an $ATTI \leq 1$ implies that the aggregation will cause more energy consumption than it saves, and thus the path should be avoided.

$$ATTI = \frac{\Delta E_{lact}^{saved}}{\Delta E_{lact}^{added} + \Delta E_{ltran}^{added}} = \frac{(u_l - 1) \cdot \bar{E}_{lact}}{p \cdot \bar{E}_{lact} + q \cdot P_t \cdot t_{tr}} \quad (21)$$

LARI is used to identify which paths have aggregation potential. ATTI determines which paths are worth aggregating when there are several potential paths. To illustrate this, Figure 4 shows the roles of the LARI and the ATTI in energy-efficient routing decisions. On the left, the concept of link activation reuse is illustrated. Path 1 and Path 2 (green lines shown in the figure) activate new links, resulting in a low LARI value ($LARI=0$), whereas Path 3 (orange lines shown in

the figure) achieves partial reuse ($LARI=1/3, 1/2$), yielding a relative high LARI value, reflecting a moderate sharing of link activation energy. On the right, the impact of ATTI is highlighted by comparing two candidate paths. The bottom path (green and orange lines shown in the figure) reuses more activated links. It incurs a large detour, leading to excessive additional transmission energy and a low ATTI value, indicating that the energy-saving benefit is offset. The top path provides a better energy trade-off with limited detour cost, resulting in $ATTI = 0$ and making it more favorable for energy-efficient routing. By jointly considering LARI and ATTI, we can balance energy reuse potential and transmission cost, enabling dynamic and effective energy-aware path aggregation strategies.

B. Energy-Efficient Algorithms: PA-ESA and EB-ESA

The section introduces the PA-ESA and EB-ESA algorithms. The parameters used in the algorithms are listed in Table 3. PA-ESA inputs are shown in Table 4. The algorithm starts when a service request $r(s_r, d_r, b_r, c_r)$ arrives. Based on the ephemeris table and t_s , visible satellites and potential links can be determined, and the graph G can be obtained from the ephemeris table. We first compute the shortest path p_0 and then verify its validity (line 3). This path is used as a reference in later comparisons. Subsequently, the algorithm computes a set of k candidate paths $k_s = \{p_1, p_2, \dots, p_k\}$ using the k-shortest path algorithm (line 7). For each link in a path, the algorithm checks whether the link has sufficient available bandwidth and whether both satellites have adequate remaining energy to activate the link. If any condition fails, the path will be deleted. For feasible paths, if a link is reused (already activated), its additional energy cost is zero; otherwise, the required activation energy E_{lact} will be added to the total. Next, for each path $p \in K_s$, LARI is computed as Eq. (20) (line 13). For each path compared to the path p_0 , we can calculate the LARI, ATTI, and energy consumption of the possible paths (lines 15). If the candidate set is non-empty, the path with the high LARI and high ATTI is preferred (line 18). The bandwidth resources in the selected path are then used to allocate to the service (line 21), and link states, i.e., bandwidth and residual energy, are updated accordingly (lines 22-27). If no feasible path is found, the service request fails. In the dynamic arrival scenario of

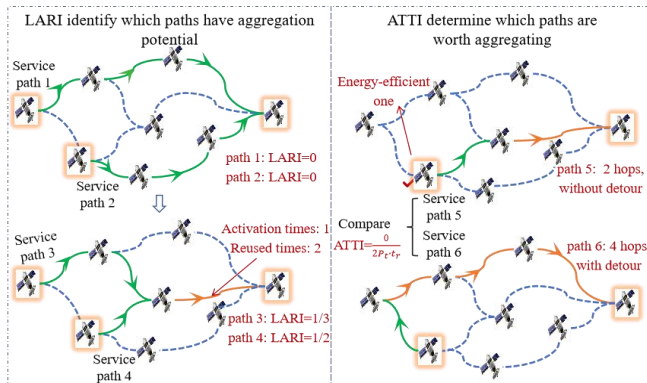


FIGURE 4. Illustration of the LARI and ATTI in the PA-ESA.

TABLE 3. Parameters definition of symbol.

Symbol	Definition
E_{ini}	Constant, initial energy of each satellite.
E_{thr}	Constant, minimum residual-energy threshold.
E_{lact}	Constant, OISL activation energy for an OISL.
p_{tx}	Constant, transmission power of OISL.
p_{hold}	Constant, OISL holding power.
E_{energy}	Variable, total energy consumption of a path.
p_e	Variable, the path for successfully allocated service.
$BW[i][j]$	Variable, the bandwidth of links.
Feasible	Variable, the set of feasible candidate paths.
E_T	Variable, total energy consumption of services.
$N_{success}$	Variable, numbers of successfully allocated services.
B_{occ}	Variables, total occupied bandwidth.

requests, each successfully allocated service is associated with a holding time, c_r/b_r . When a service departs, the allocated bandwidth is released. If an OISL carries no remaining service, it will be deactivated (or switched to sleep mode) to save energy (lines 31-35).

As shown in Table 5, the EB-ESA algorithm has the same inputs and outputs as the PA-ESA algorithm. After executing the k -shortest path algorithm, k candidate paths can be obtained (line 3). By traversing each link in the path p , the algorithm checks whether the available bandwidth and the residual node energies satisfy the bandwidth requirement b_r and the energy threshold E_{thr} , respectively (lines 7-12). If any link fails to meet these conditions, the path is deemed invalid and skipped (lines 8-11). Different from the PA-ESA algorithm, EB-ESA considers both energy efficiency and energy balancing. For each feasible path, the algorithm calculates its total energy consumption, LARI, and ATTI (lines 17-21), and then also calculates the minimum residual energy E_{low} along the path to evaluate

TABLE 4. The PA-ESA algorithm.

Input: $G(V, L), (E_{ini}, E_{thr}, E_{lact}, p_{hold}, p_{tx}), r(s_r, d_r, b_r, c_r)$.	
Output: $E_T, N_{success}, B_{occ}$.	
1:	$E_T = 0, B_{occ} = 0, N_{success} = 0, E_node[] = E_{ini}$
2:	For $r \in R$ do
3:	$p_0 \leftarrow \text{Dijkstra}(G, s_r, d_r)$
4:	If not isValid(p_0, r)
5:	Continue end if
6:	$E_{ref} \leftarrow \text{computeEnergy}(p_0)$
7:	$K_s \leftarrow \text{KShortestPaths}(G, s_r, d_r, k)$
8:	Feasible $\leftarrow []$
9:	For $p \in K_s$ do
10:	If not isValid(p, r, E_{thr}) then continue end if
11:	Reused_links $\leftarrow \text{countReusedLinks}(p)$
12:	Energy $\leftarrow \text{computeEnergy}(p, p_{hold}, p_{tx}, c_r/b_r)$
13:	LARI $\leftarrow$ according to Eq. (20)
14:	ATTI $\leftarrow$ according to Eq. (21)
15:	Feasible.append ($p, \text{LARI}, \text{ATTI}, \text{Energy}$)
16:	End for
17:	If Feasible $\neq []$ then
18:	Sort Feasible (ATTI, LARI, Energy)
19:	$p_e \leftarrow \text{Feasible}[0].p$
20:	For $(i, j) \in p_e$ do
21:	$BW[i][j] \leftarrow BW[i][j] - b_r$
22:	$E_link \leftarrow (p_{hold} + p_{tx}) * c_r/b_r$
23:	If isNewLink(i, j) do
24:	Energy $\leftarrow \text{Energy} + E_{lact}$
25:	$E_link \leftarrow E_link + E_{lact}$ end if
26:	$E_node[i] \leftarrow E_node[i] - E_link / 2$
27:	$E_node[j] \leftarrow E_node[j] - E_link / 2$ end for
28:	$E_T \leftarrow E_T + \text{Energy}$
29:	$B_{occ} \leftarrow B_{occ} + b_r$
30:	$N_{success} \leftarrow N_{success} + 1$
31:	For $(i, j) \in p_e$ do //Service departure
32:	$BW[i][j] \leftarrow BW[i][j] + b_r$
33:	If $BW[i][j] == C_{ij}$ do
34:	Deactivate (i, j) and update E_node and link state; end if end for
35:	Else
36:	Block the service request; end if end for
37:	Return { $E_T, N_{success}, B_{occ}$ }

the impact of this path on energy balance (line 20). All feasible paths and their associated metrics are recorded in the Feasible set (line 21). Path selection then follows a prioritized judgement. If there is a path that has both a high ATTI and a high LARI at the same time, then select the path and add it to the Candidates set (line 25). If multiple candidates exist, the path with the largest E_{low} is selected as p_e to avoid bottleneck node depletion (line 27). The energy consumption is recorded based on the selected path, and the

TABLE 5. The EB-ESA algorithm.

Input: $G(V, L), (E_{ini}, E_{thr}, E_{lact}, p_{hold}, p_{tx}), r(s_r, d_r, b_r, c_r)$.	
Output: $E_T, N_{success}, B_{occ}$.	
1:	$E_T = 0, B_{occ} = 0, N_{success} = 0, E_node[] = E_{ini}$
2:	For $r \in R$ do
3:	$K_s \leftarrow \text{K Shortest}(G, s_r, d_r, k)$
5:	$p_0 \leftarrow$ the first K_s
6:	Feasible $\leftarrow []$
7:	For $p \in K_s$ do
8:	Is_valid $\leftarrow \text{True}$
9:	For $(i, j) \in p$ do
10:	If $BW[i][j] < b_r$ or $E_node[i] < E_{thr}$ or $E_node[j] < E_{thr}$ then
11:	Is_valid $\leftarrow \text{False}$
12:	Break
13:	End if end for
14:	If Is_valid is True then
15:	Reused_links $\leftarrow \text{countReusedLinks}(p)$
16:	New_links $\leftarrow \text{countNewLinks}(p)$
17:	Energy $\leftarrow \text{computeEnergy}(p, p_{hold}, p_{tx}, c_r/b_r)$
18:	LARI $\leftarrow$ according to Eq. (20)
19:	ATTI $\leftarrow$ according to Eq. (21)
20:	$E_{low} \leftarrow \min \text{LinkEnergy}(p)$
21:	Feasible.append ($p, \text{LARI}, \text{ATTI}, \text{energy}$)
22:	End if end for
23:	If Feasible $\neq []$ then
24:	Sort Feasible (ATTI, LARI, and Energy)
25:	Candidates $\leftarrow p$ with high LARI and high ATTI
26:	If Candidates ≥ 1 then
27:	$p_e \leftarrow p$ with maximum E_{low}
28:	Else
29:	$p_e \leftarrow \text{Candidates}[0]$ end if
30:	For $(i, j) \in p_e$ do
31:	$BW[i][j] \leftarrow BW[i][j] - b_r$
32:	$E_link \leftarrow (p_{hold} + p_{tx}) * c_r/b_r$
33:	If isNewLink(i, j) do
34:	Energy $\leftarrow \text{Energy} + E_{lact}$
35:	$E_link \leftarrow E_link + E_{lact}$ end if
36:	$E_node[i] \leftarrow E_node[i] - E_link / 2$
37:	$E_node[j] \leftarrow E_node[j] - E_link / 2$
38:	End for
39:	$E_T \leftarrow E_T + \text{Energy}$
40:	$B_{occ} \leftarrow B_{occ} + b_r$
41:	$N_{success} \leftarrow N_{success} + 1$
42:	For $(i, j) \in p_e$ do //Service departure
43:	$BW[i][j] \leftarrow BW[i][j] + b_r$
44:	If $BW[i][j] == C_{ij}$ do
45:	Deactivate (i, j) and update E_node and link state; end if end for
46:	Else
47:	Block the service request; end if end for
48:	Return { $E_T, N_{success}, B_{occ}$ }

relevant parameters are updated accordingly (lines 32-37). The remaining steps are similar to those in the PA-ESA algorithm.

C. TIME COMPLEXITY OF PA-ESA AND EB-ESA ALGORITHMS

The time complexity of the PA-ESA algorithm consists of three main components: *i*) the *k*-shortest path computation, i.e., $O(k(|L|\log|V|+|V|^2))$; *ii*) bandwidth and length in hops; and *iii*) link traversal for energy consumption sorting, i.e., $O(k\log k)$. The overall time complexity is dominated by the path search operation, which can be expressed as $O(k(|L|\log|V|+|V|^2)+k|L|+k\log k)$. Furthermore, EB-ESA introduces an extra cost of $O(k|L|)$ to evaluate the minimum residual energy B_{low} , among nodes on each path. Although its complexity remains $(k(|L|\log|V|+|V|^2))$, EB-ESA incurs slightly higher computational overhead during the path selection.

V. SIMULATION RESULTS

A. SIMULATION SETTINGS

To evaluate the proposed solutions, we employed the Walker-Delta star constellation, a standard benchmark in constellation design, using AGI's Satellite Tool Kit (STK) simulator. The candidate OISLs at each snapshot are constructed according to the time-varying physical visibility and geometric conditions of the satellite constellation. For STK simulations, the visibility time window of each candidate OISL is first determined during topology generation. At each snapshot time, an OISL is considered available if the snapshot falls within its corresponding visibility window; otherwise, it is considered unavailable. Therefore, the continuously varying satellite geometry and OISL visibility are discretized into a sequence of time-dependent network topologies. Detailed constellation data, including satellite connectivity and OISL duration, were exported from STK. The topology matrix is generated by sampling 20 consecutive snapshots of the Walker-delta constellation listed in Table 6, which is constructed in STK, over the time interval from 4:00 to 5:35 with 5-minute intervals. The ILP model was solved via Python 3.10.11 utilizing the Gurobi solver with a prescribed mixed-integer programming optimality gap of 5%, where a near-optimal solution was treated as an offline reference. To maintain a tractable ILP formulation while preserving the sparse connectivity of satellite networks, an 15-satellite topology with a maximum node degree of four is used primarily for evaluating the ILP formulation, using the parameters listed in Table 7. To further evaluate the applicability and scalability of the proposed algorithms in larger networks, we consider a Walker-Delta constellation with 1080 satellites in dynamic scenarios. We developed a C++ event-driven simulator integrated with the snapshots obtained from STK. The snapshots served as topology samples in the network simulator, with service arrivals

TABLE 6. Setting of dynamic algorithms.

Parameter	Value
Constellation	Walker-Delta star
Number of satellites	1080
Orbital planes	72
Satellites per orbit	15
Altitude	750 km
Inclination	53°
Phase increment	0
Numbers of ground stations	30
Simulation start time	04:00:00.000
Simulation stop time	06:00:00.000
Orbit period	2 hours
Time step	20 seconds
Orbital propagation	Two-body model
OISL establishment	line-of-sight geometric visibility
Snapshot duration	5 min [44]
OISL bandwidth	10 Gbit/time slot
Numbers of requests	10000
Source node in requests	A random ground station
Destination node in requests	A random ground station
Bandwidth requirement	100 Mbit/time slot
Link activation energy (E_{ij}^{act})	210 J/activation
Transmission power (P_{ij}^{tx} or P_{ij}^{hold})	30 J/time slot
Holding power (P_{ij}^{hold})	30 J/time slot
Initial energy per satellite	100000 J
Energy threshold per satellite	200 J
<i>k</i> number of paths	4
Traffic loads	{200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800}

TABLE 7. Setting of ILP parameters.

Parameter	Value
Number of satellites	15
Maximum satellite degree	4
Wavelength number	4
Time slot number	60
Bandwidth	10 Gbit/time slot
Link activation energy	210 J/activation
Transmission energy per slot	30 J/time slot
Energy threshold per satellite	100000 J
Request number	{30, 40, 50, 60}
Request bandwidth	100-300 Mbps
Request time slot	5-15 time slots

TABLE 8. Comparison of baselines and the proposals.

Purpose	Algorithm	Energy Aware	Aggregation	Link Re-use	Energy Balance	Trade-off
Energy Saving	PA-ESA	√	√	√	-	√
	ETGR	√	√	√	-	×
	EA-K	√	×	×	-	×
	K	×	×	×	-	×
Energy Balancing	EB-ESA	√	-	-	√	√
	EB	√	-	-	√	×

following a Poisson distribution (i.e., arrival rate = 0.04) and holding times following an exponential distribution (i.e., rate = 0.03). Based on the overview of component power in Ref. [44], the relevant power parameters can be expected to vary within a reasonable bound. All simulations were

conducted on a computer with an Intel Core i5-8250U CPU and 40GB RAM. The specific parameters are summarized in [Table 6](#).

To evaluate the performance of the proposed PA-ESA and EB-ESA, four baselines were introduced for comparison. To provide a comprehensive overview, the feature comparisons between our proposed algorithms and these baselines are summarized in [Table 8](#). Specifically, the first three baselines (i.e., i-iii) focus on energy saving to benchmark PA-ESA, while the remaining one (i.e., iv) aims at energy balancing to evaluate EB-ESA:

i) *Energy-efficient Traffic-Grooming Routing (ETGR) algorithm*: This baseline represents the representative green traffic grooming routing concept in OSNs [45] published in 2024. Following its design principles, ETGR prefers the paths with high bandwidth utilization for traffic grooming and adopts the lowest energy-consumed path when multiple options exist.

ii) *Baseline Energy-Aware K (EA-K) algorithm*: This baseline prefers paths with the lowest energy consumption, subject to a predetermined energy threshold for each satellite. To mitigate resource congestion, it incorporates a fallback part that randomly selects an available alternative path ($k=4$) if the primary low-energy links are saturated.

iii) *Baseline K algorithm*: As a traditional path calculation algorithm, this baseline employs a traditional k -short path ($k=4$) to select minimum-hop paths without energy considerations.

iv) *Baseline Energy-Balanced (EB) algorithm*: This baseline identifies k candidate paths with the maximum residual energy. It utilizes a degradation to randomly select alternative paths when the high-residual-energy paths occur congestion.

Based on the above baselines for the PA-ESA and EB-ESA algorithms, we enable a comprehensive evaluation across multiple metrics, including Blocking Probability (BP), Hop Count (HC), Energy Consumption (EC), Average Energy Consumption per Service (AECS), Average Energy Consumption per Node (AECN), and the Coefficient of Variation (CV) of satellite energy consumption. To present the robustness of these performances, simulation results were conducted with the mean values and 95% Confidence Intervals (CI), which are presented in [Figure 6](#) and [Figure 7](#).

B. RESULTS OF NETWORKS

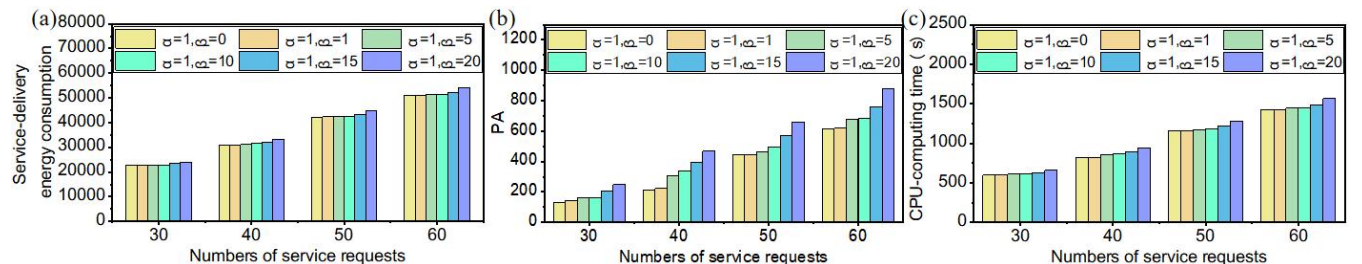


FIGURE 5. Numerical results of the objective under different numbers of requests (i.e., 30, 40, 50, and 60), in terms of (a) energy consumption, (b) PA, (c) CPU-computing time of solving the objective.

1) NEAR-OPTIMAL RESULTS

Since the service requests are assumed to be known in advance in the ILP for static resource allocation, its results are used as a near-optimal reference for the formulated objective under static request conditions, while the proposed algorithms are evaluated under dynamic request arrivals. [Figure 5](#) illustrates the performance of the proposed objective under different numbers of service requests (30, 40, 50, and 60) for the two weighting factors α and β . As shown in [Figure 5 \(a\)](#), the service-delivery energy increases almost linearly with the number of service requests for all cases of α and β . This trend is suitable since more service requests require transmission resources and activate more links. When $\alpha=1$ and $\beta=0$, the objective function emphasizes energy saving, considering the lowest energy consumption. Interestingly, when $\alpha=1$ and $\beta=1$, the energy consumption remains almost identical to that obtained with $\alpha=1$ and $\beta=0$. This indicates that introducing a moderate degree of path aggregation does not impose a noticeable energy penalty, while still encouraging the reuse of established paths. As β further increases, however, the energy consumption gradually increases relative to the energy-efficient solution with $\alpha=1$ and $\beta=0$. This is because a larger β assigns greater importance to path aggregation, which can cause some traffic demands to detour from shorter paths to increase path sharing, thereby incurring additional energy consumption. These results show a trade-off between path aggregation and energy saving: moderate path aggregation can be achieved without substantially compromising energy efficiency, whereas excessive emphasis on path aggregation may force services onto longer routes and offset its potential energy-saving benefits.

In [Figure 5 \(b\)](#), the PA metric consistently increases with both an increasing number of requests and a larger aggregation weight β . When β increases from 1 to 10, a larger PA portion is achieved, indicating that more service requests are allocated through common links. This verifies that the designed objective can achieve the enhancement of path aggregation by adjusting β . As illustrated in [Figure 6 \(c\)](#), the CPU-computing time also increases with higher traffic loads. A larger β leads to a longer solving time because the optimization model places greater emphasis on path aggregation, resulting in a more constrained solution space and increased computational complexity.

Overall, the above results reveal a clear trade-off among path aggregation, energy efficiency, and computational

complexity. It is obvious that increasing β improves path aggregation at the cost of slightly higher energy consumption and longer optimization time. Therefore, the weighting parameters provide flexibility for network operators to balance energy-saving objectives and traffic-consolidation requirements according to practical scenarios.

2) RESULTS OF THE PA-ESA AND EB-ESA

i) BP

As shown in **Figure 6 (a)**, the blocking probability of all algorithms increases with the traffic load. Note that in this paper, the BP corresponds to the service drop rate, as any blocked request fails to be allocated the necessary resources and is consequently dropped. The algorithms were evaluated under varying traffic loads ranging from 200 to 800 with a step size of 50. This behavior is expected because increasing traffic demands gradually consume the available network resources, resulting in a higher probability of failed requests. Among all compared algorithms, the PA-ESA can achieve the lowest blocking probability throughout the entire traffic-load range. The performance advantage becomes obvious under heavy traffic conditions. Specifically, the maximum blocking probability decreased by 0.44% compared to ETGR, by 1.7% compared to EA-K, and by 2.5% compared to K. These results indicate that the path aggregation can reduce blocking probability by consolidating services onto existing active paths, thereby reducing the number of newly activated links and alleviating network congestion. Furthermore, the CI remains relatively narrow across all traffic loads, illustrating that PA-ESA exhibits stable performance under different topologies.

Figure 6 (b) shows the comparison of EB-ESA with the baseline energy-balancing scheme. It can be observed that both algorithms experience increasing blocking probability as the offered traffic grows. However, EB-ESA consistently outperforms Baseline EB, especially under medium and high traffic loads. The largest observed performance gain

reaches approximately 0.62%, indicating that the proposed energy-aware path selection strategy can effectively maintain network service capability while simultaneously considering energy-efficient objectives. In addition, the confidence intervals of EB-ESA are generally comparable to those of EB, suggesting that the proposed strategy does not introduce additional performance instability.

ii) HC

Figure 6 (c) shows the average hop-count results. For PA-ESA, ETGR, and EA-K, the hop count remains relatively stable as traffic load increases, indicating that these algorithms can maintain efficient routing paths even under heavier network loads. Compared with ETGR, PA-ESA achieves a maximum hop-count reduction of 6.31% (a reduction of approximately 0.28 hops). More significant improvements are observed against EA-K (up to 21.1% or 1.12 hops), while a slight reduction of 4.1% (0.19 hops) is achieved compared to K. The reduction in hop count suggests that the path aggregation not only improves resource utilization but also promotes the reuse of efficient routing paths, thereby limiting unnecessary path elongation.

As shown in **Figure 6 (d)**, the average hop count of EB-ESA remains consistently lower than that of the EB. The maximum gap between the two schemes reaches approximately 0.62 hops. This indicates that the proposed energy-aware routing mechanism can simultaneously balance energy consumption and routing efficiency without introducing excessive path stretching. Moreover, both algorithms exhibit relatively flat hop-count curves across all traffic loads, suggesting that route lengths are only marginally affected by increasing network congestion.

iii) EC

As observed in **Figure 7 (a)**, the EC of all algorithms, including PA-ESA, ETGR, EA-K, and K, shows a decreasing trend as the traffic load increases. This is typically attributed to higher resource consolidation under heavier traffic loads. Notably, the proposed PA-ESA

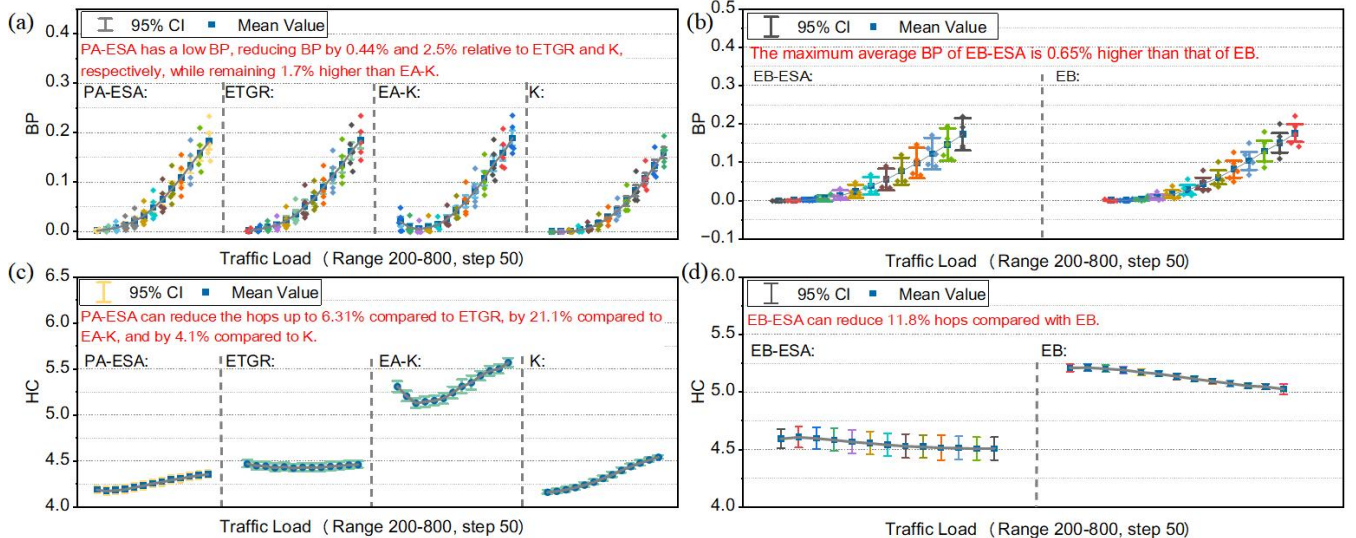
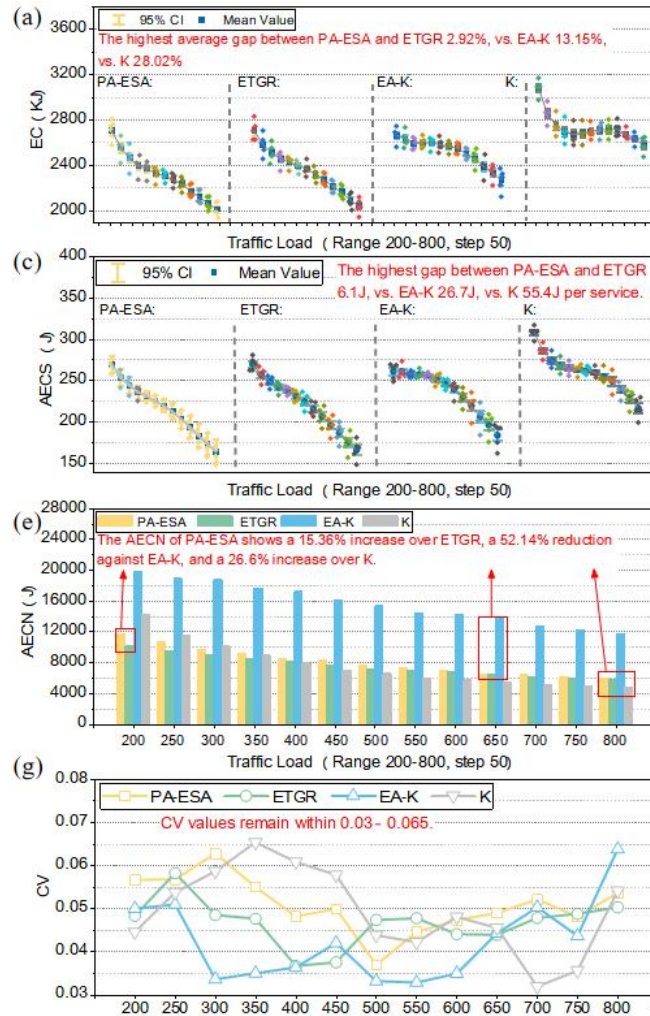


FIGURE 6. Comparison of BP and HC performance across dynamic traffic loads bounded by the 95% CI. Subplots (a) and (c) denote the BP and HC for the energy-saving (i.e., PA-ESA). Subplots (b) and (d) outline the corresponding BP and HC for the energy balancing (i.e., EB-ESA).

consistently achieves the lowest EC across the entire traffic range. Specifically, PA-ESA outperforms ETGR with a maximum average gap of 2.92% to save the total energy. Although ETGR achieves the energy saving by reusing existing OISLs, it introduces additional transmission energy due to excessive traffic concentration and path detours. In contrast, PA-ESA employs the proposed ATTI metric to evaluate whether the activation-energy saving outweighs the additional transmission cost, thereby achieving the lowest overall energy consumption. PA-ESA shows energy-saving advantages, yielding a maximum average gap of 13.15% against Baseline EA-K and a 28.02% reduction compared to Baseline K. **Figure 7 (b)** illustrates the EC comparison between EB-ESA and Baseline EB. Similar to the PA, the total energy consumption decreases with increasing traffic loads. The proposed EB-ESA consistently remains below the curve of EB, securing a maximum average energy-saving gap of 3.78%, which validates the effectiveness of the EB-ESA optimization in reducing overall grid or network overhead.

iv) AECS

Figure 7 (c) shows the AECS, which is defined as the



ratio of the total energy consumption to the total number of successfully accommodated requests to evaluate the energy efficiency from a service perspective. The AECS decreases from approximately 270J to 150J as traffic load increases, underscoring that energy costs are amortized over a larger volume of active services. PA-ESA maintains its superior performance here. The maximum AECS gap between PA-ESA and ETGR is marginal, restricted to 6.1J per service. However, compared to Baseline EA-K and Baseline K, PA-ESA reduces energy consumption by up to 26.7J and 55.4J per service, respectively, making it highly suitable for energy-efficient, per-service provisioning. **Figure 7 (d)** presents trends of EB-ESA and EB. At lower-to-mid traffic loads, EB-ESA secures a distinct advantage, achieving a maximum positive gap of 9.2J per service. Conversely, at specific high-load instances, the gap drops to a minimum of 32.9J per service (where Baseline EB slightly undercuts EB-ESA). This fluctuation indicates that under the EB mechanism, per-service energy efficiency is highly sensitive to dynamic traffic fluctuation and routing reconfiguration at high utilization thresholds.

v) AECN

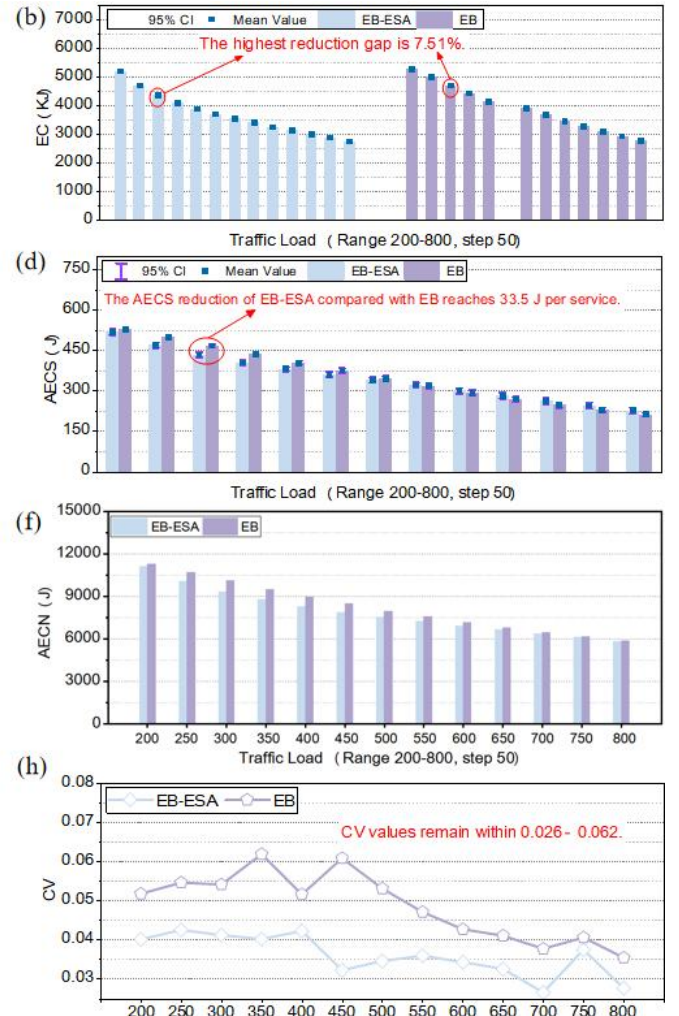


FIGURE 7. Performance under varying traffic loads (ranging from 200 to 800 with a step of 50). The left column (a, c, e, g) presents the benchmark results for the energy-saving proposals (i.e., PA-ESA), while the right column (b, d, f, h) presents the energy-balancing proposal (i.e., EB-ESA).

Figure 7 (e) and **(f)** show the AECN across various traffic loads, which was calculated as the ratio of EC to the total number of used satellites. It is easy to observe that path aggregation may concentrate services on certain specific satellites, thereby increasing their energy consumption. Thus, we designed the AECN to reflect the energy balancing capability across satellites. In the energy-saving part, PA-ESA shows the lowest trend of AECN in **Figure 7 (e)**, meaning that the average energy burden per utilized satellite was reduced while maintaining overall network efficiency. The performance gap of AECN varies under different traffic conditions. At 200 Erlang, the AECN of PA-ESA outperformed that of ETGR by increasing 15.36%. At 650 Erlang, it decreased by 52.14% compared to EA-K. At 800 Erlang, it increased by 26.6% compared to the baseline K. This is because the network is unsaturated with abundant idle capacity at a low load (i.e., 200 Erlang). Thus, the aggregation focus of ETGR can easily deactivate entire regions of the topology to save energy, making PA-ESA show a minor 15.36% energy overhead in exchange. As the traffic scales to a moderate load (i.e., 650 Erlang), routing congestion begins to occur. The EA-K suffers from topological fragmentation by routing around low-energy nodes, easily triggering multi-hop paths with redundant OISL activations. The PA-ESA, benefited from LARI and ATTI, suppresses unnecessary activations and consolidates fragmented flows.

Figure 7 (f) shows the AECN of EB-ESA and EB. We can observe that as the traffic load increases from 200 to 800, the AECN for both algorithms shows a decreasing trend. This is because a greater number of requests were successfully allocated resources by occupying more nodes under higher traffic loads. The energy consumption was effectively distributed across a broader range of request numbers, leading to the dilution of average per-node energy indicators. The proposed EB-ESA outperforms the EB across all traffic loads, with a certain energy-saving gap under low-to-medium loads. This superiority is caused by the integrated LARI and ATTI. EB mainly relies on the maximum residual energy metric and reacts to congestion via path degradation, which easily triggers fragmented alternative paths that repeatedly use redundant OISL activations.

vi) *CV*

To further evaluate the balance of energy consumption among utilized satellites, we introduce the CV of satellite energy consumption, defined as

$$CV = \frac{\sigma_E}{\bar{E}} \quad (22)$$

where $\bar{E}$ and σ_E denote the mean and standard deviation of the energy consumption among the utilized satellites, respectively. A lower CV indicates a smaller relative dispersion of energy consumption and thus a more balanced energy consumption distribution.

Figure 7 (g) and **Figure 7 (h)** further compare the CV of satellite energy consumption under different traffic loads. As shown in **Figure 7 (g)**, the CV values of PA-ESA and

ETGR remain relatively stable over the considered traffic-load range, whereas EA-K and K exhibit more obvious fluctuations. This indicates that the energy consumption distribution of the former schemes is less sensitive to traffic-load variations, while the latter schemes may concentrate energy consumption on different subsets of satellites as the traffic load changes. As shown in **Figure 7 (h)**, EB-ESA achieves a lower CV than EB across the considered traffic loads, indicating that EB-ESA provides a more balanced energy consumption distribution among the utilized satellites. Overall, these results can be combined with the AECN evaluation by showing that energy efficiency and energy-consumption balance are distinct aspects of the energy performance.

VI. CONCLUSIONS AND FURTHER RESEARCH

This study investigates energy-efficient OISL allocation in OSNs by jointly considering path aggregation and energy consumption during service delivery. An optimization problem is formulated to balance the benefits of link reusing against the energy cost associated with OISL activation and transmission. To characterize this trade-off, two indexes, namely LARI and ATTI, are introduced to quantify the degree of link reusing and the energy-saving benefit relative to the additional transmission energy caused by path aggregation, respectively. Based on these indexes, two energy-efficient algorithms, PA-ESA and EB-ESA, are developed for OISL allocation. The simulation results illustrate that PA-ESA can reduce both energy consumption and hop count while maintaining a relatively small impact on blocking probability. It also indicates that path aggregation can improve resource utilization and routing efficiency by increasing the reuse of established OISLs. However, the accompanying increase in AECS and AECN shows that path aggregation introduces additional resource and energy costs. Therefore, the degree of path aggregation should be appropriately selected to balance link reuse and energy efficiency. As future work, we will investigate energy consumption over multiple orbital cycles by considering time-varying traffic patterns and energy supply to support long-term energy optimization.

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