Analysis of LEO-Satellite Fronthaul Schedulers

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Abstract—**Low Earth Orbit (LEO) satellite networks (LSNs), such as Starlink, OneWeb, and Kuiper, are developing rapidly, providing a new and more geographically equal possibility for internet access. LSNs consist of two parts: fronthaul is the connection between users and satellite constellations; backhaul links the constellations to the core network. The large scale of the constellations and high movement speed of LEO satellites make the scheduling problem distinct from that of geostationary networks. This paper focuses on the design concept of fronthaul scheduling algorithms for LSNs. As objectives of the scheduling algorithms, low latency, high capacity, wide coverage, energy efficiency, and fault tolerance are considered; the impact of various satellite parameters on these goals are discussed, including Angle of Elevation, direction, launch date and sunlit status. Since these factors have both positive and negative impacts on the objectives of scheduling, the design of scheduling algorithms involves trade-offs among different goals.**

Index Terms—**LEO satellite networks, LSNs, scheduling, Starlink**

1. Introduction

Low Earth Orbit (LEO) satellite networks, abbreviated as LSNs, are rapidly developing network technologies that provide commercial civilian network services. Currently, the three largest-scaled LSN projects include Starlink, OneWeb, and Kuiper [1], among which Starlink is already serving over 2.6 million users [2].

The altitude of LEO is below 2,000 km, compared to geostationary orbit (GEO) with 35,786 km. [3] Its comparatively short distance to ground stations allows a significant lower latency of ground-satellite communication, and less cost of satellite deployment. Relative to terrestrial networks, the service coverage provided by LSNs is wider and more independent of the geographic environment. Especially for maritime and remote areas, where ground-based stations struggle to cover, LSNs can offer much more affordable internet services than GEO-satellite based communication.

On the other hand, lower orbits lead to a limited terrestrial coverage by each single LEO satellite, as well as a higher velocity. The orbital period of LEO satellites typically ranges from 10 to 50 minutes [4], corresponds to a travel speed of ~27,000 km/h [3], which is over 30 times of the cruising speed of modern airliners. The scheduling between ground-stations and LEO satellite must thus be designed specially to cape with the fast and constant changes of the network topology. With these limitations caused by the low orbital altitude, one single LEO satellite is not helpful to provide network serviced. LSNs require thousands of LEO satellites to cooperate, in order to achieve efficiency and wide service area.

Table 1 summarizes the current and planned status of LEO satellite constellations of Starlink, OneWeb and Kuiper.

TABLE 1: Constellation design and status of Starlink, OneWeb and Kuiper

Project	Number of Satellites		Orbit altitude
	In operation	Planned	
Starlink	5564 [5]	42000 [6]	340-550 km [7]
OneWeb	632 [8]	6372 [9]	~1200 km [10]
Kuiper	2 [11]	3236 [12]	590-639 km [12]

This paper first provides an overview of the structure of LSNs, then focuses on the scheduler for user-satellite connections, highlighting the differences between LSNs scheduling and the relatively static terrestrial and GEO-satellite-based networks.

2. Architecture of LSNs

With the LEO satellites playing a central role, LSNs can be divided into two main parts: fronthaul, which is the connection between users and the LEO satellite constellation, and backhaul, through which the constellation connects to the core network. The backhaul involves the connection between LEO satellites and the ground stations, and from these ground stations to the core network through Points of Presence (PoPs).

Figure 1 illustrates the basic architecture of LSNs. More details about each component are described in Section 2.1; Section 2.2 expands on the different topology structures of connections between LEO satellites.

2.1. Composition of LSNs

As shown in Figure 1, components of an LSN include user terminals, LEO satellites, ground stations, PoPs and the core network. The functionality and technical configuration of each component can vary across different commercial projects and user group characteristics (e.g. users accessing the network services at sea versus those from remote areas on land). This paper primarily considers the configurations of Starlink for terrestrial network users [13], which is the most common scenario in current practical applications.

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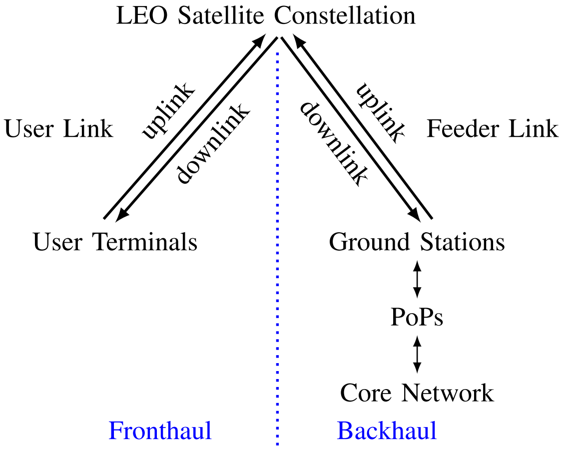

Figure 1: The Architecture of LSNs

In an LSN, user terminals, or dishes according to their common shape, communicate with LEO satellites, enabling individual or household networks to connect to the LSN. Each user terminal only has sight of a limited range of Angle of Elevation (AoE) of the satellites, and connects to only one of the LEO satellites in sight at the same time.

In contrast, each LEO satellite often connects to multiple user terminals simultaneously. This is reasonable considering their quantities: Starlink for instance utilizes less than 5.6×10^3 LEO satellites to serve over 2.6×10^6 users, as mentioned in the introduction.

Ground stations are also referred to as gateways. Their geographical distribution is designed strategically to ensure a high global coverage, while taking into account the different regulation of various countries and regions. The distribution of ground stations for commercial LSNs is usually not published, but according to an unofficial statistical report [14], Starlink now utilizes at least 150 ground stations, distributed across the globe.

LEO satellites connect to user terminals and ground stations through radio waves, with the frequency varying for different projects and applications [15]. The link between ground stations and satellites is called feeder link; the link between user terminals and satellites is referred to as user link. Uplink refers to the channels for sending signals from user terminals or ground stations to LEO constellations; downlink refers to the link from satellites to ground components. The connections between ground stations and PoPs, and those between PoPs and the core network, are mostly via optical fiber cables.

This paper focuses on fronthaul scheduling of LSNs, i.e. at any given moment, which satellite should each user terminal be connected to. This is one of the most complicated and distinctive processes of the scheduling within LSNs compared to other networks and influences user experience directly.

2.2. Topology Structure of Connections between Satellites

Inter-satellite connectivity is a key variable of LSNs' topology structure. The links within a LEO satellite constellation can either be set directly via laser or radio connection, or relayed by a ground station. The former is called inter-satellite links (ISLs). The scenario without ISLs and purely relies on ground station relayed links is called bent-pipe (BP) connectivity.

It is possible to provide a low-latency internet connection without ISLs [16], [17]. However, compared to BP-based LSNs, incorporation of ISLs can bring even lower latency, increase the network throughput and the resilience against bad weather, as well as provide more equitable network services with the same number of available ground stations [17].

Due to regulatory issues, ISLs have not been adequately integrated in existing LSN projects: ISLs via radio spectrum require licenses from the authorities, while laser based ISLs require the use of silicon-carbide components with a high melting point, thus possibly violating the "burn on reentry" requirement for LEO satellites [17]. Currently, Starlink is increasingly adopting ISLs in the constellations, and numerous researches on traffic scheduling algorithm for ISLs are carried on.

3. Fronthaul Scheduling for LSNs

Although the fronthaul scheduling algorithms of the existing and planned commercial LSNs are not open-source, researches have been conducted on the factors that should be considered in the design of scheduling methods [1], [13], the development of specific algorithms [18], [19], and the properties of currently operational scheduling algorithms of Starlink [13], [20].

Scheduling in LSNs includes many aspects, and the system models vary significantly depending on the extent to which ISLs are utilized. This paper focuses on the scheduling of satellites as a scarce resource for user link, which is one of the most critical parts of scheduling under the BP model. This section is organized as two Subsections: in Subsection 3.1, the objectives of scheduling algorithms are listed; Subsection 3.2 introduces various factors that should be considered in the fronthaul scheduling algorithms, and their impact on the goals considered in the previous subsection.

3.1. Goals of Scheduling Algorithms

The objectives of scheduling algorithms for LSNs include:

Low latency. Latency refers to the round-trip time (RTT) of a packet from the sender to the receiver. It measures how responsive the network connection is, and influences user experience directly. Low latency is a critical goal of network services, especially for real-time scenarios, such as online gaming and video conferencing. Starlink sets its goal to stable 20-millisecond median latency and considers the fronthaul scheduling as the major focus to improve the response speed of its service [2]. As of March 2024, Starlink provides most terrestrial regions an RTT between 25 to 75 milliseconds [2], [21], corresponding to that within North America for geostationary-based network services with distances ranging from 1000 km to 4000 km, according to a linear regression result based on observational data [22].

High capacity. The capacity of LSNs is limited by the number of satellites and the design of the constellations

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[23], but for operational LSNs such as Starlink, this is generally not the bottleneck of the service, but rather an abundant and underutilized resource [24]. According to an estimation model [23], the capacity of LSNs can be seen as linearly proportional to the number of satellites in operation, with each satellite providing a data rate no larger than 10 Gbps. Based on this, with currently 5564 LEO satellites in use, Starlink's capacity is limited to approximately 55.6 Tbps, compared to global internet bandwidth at 1217 Tbps in September 2023 [25]. To utilize the capacity and achieve higher bandwidth, the scheduling algorithm should balance the dataflow in the LSNs, and pay special attention to the single-point bottleneck of bandwidth on the feeder link [26].

Wide coverage. The coverage of LSNs is mostly determined by the constellation designing, but should also be considered in the scheduling process, especially for regions lacking ground stations.

Energy efficiency. Energy efficiency is especially important to LEO satellites, not only from an environmental-friendly point of view, but also due to the limited energy resources acquirable in orbit, and that the charging and discharging process reduces the satellites' life time [27]. The energy for LEO satellites is mostly solar energy, and thus whether a satellite is being sunlit can make a difference for the scheduling algorithms.

Fault tolerance. As the deployment of satellites and ground stations is more time consuming than terrestrial networking, and due to the limited number of them, LSNs are more fragile than network services. Under various types of cyber attacks, LEO satellites and ground stations can be overloaded, isolated, or put into outage, causing a cascading failure [28]. Consequently, fault tolerance should be carefully considered in the design of scheduling algorithms.

3.2. Influence Factors of Fronthaul Scheduling

With the position of satellites changing constantly, the scheduling procedure of ground-satellite links must be decided frequently. An empirical research [13] on the behavior of Starlink shows that Starlink likely utilizes a global scheduler that plans the connections between user terminals and satellites every 15 seconds. Accordingly, the scheduling for user links should be simple enough to be executed swiftly while taking the goals mentioned formerly into account in order to achieve a high quality of service (QoS).

In the following, the mechanisms of four important influence factors are discussed. These factors are analysed in the experiment by Tanveer *et al.* [13], but this paper focuses more on how they are manifested at the Starlink user end, whereas this Subsection dives deeper into the rationale and related researches of them.

3.2.1. AoE (Angle of Elevation). AoE of a satellite from some point on the earth refers to the angle between the horizontal line at that point and the line of sight pointing directly upwards to the satellite. Figure 2 illustrates the definition of it.

For satellites of the same orbit altitude, AoE decides its distance to points on the ground. From the law of

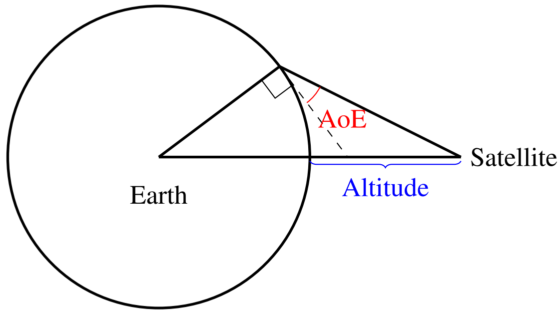

Figure 2: Angel of Elevation

cosines, the geometric relationship between them can be represented by formula 1:

$$(R+h)^2 = R^2 + d^2 - 2Rd\cos(\frac{\pi}{2}+\theta) \qquad (1)$$

Where θ represents AoE in the range of $(0, \frac{\pi}{2}]$, R is the radius of the earth (approximated as a sphere), h is the height or altitude of the satellite, and d is the distance between the observation point on the earth and the satellite. Through mathematical derivation, the expression for d as a function of AoE θ can be obtained as following:

$$d = \sqrt{h^2 + 2Rh + R^2\sin^2\theta} - R\sin\theta \qquad (2)$$

This function is strictly monotonically decreasing over $(0, \frac{\pi}{2}]$. This means that the distance between a point on the earth and a LEO satellite is always shorter for a greater AoE, and the minimum is met when $\theta = \frac{\pi}{2}$, i.e. when the satellite is directly above this point, and then the distance would be equal to the altitude of the orbit. The shorter distance brings lower latency and energy consumption, thus for user links, satellites with greater AoE for user terminal should be favoured by the scheduling algorithm.

3.2.2. Being sunlit. The current operating LEO satellites are powered by solar energy [29]. When being sunlit, they use solar energy directly, and charge the on-board batteries if there is surplus energy; during the eclipse period, their only power source is the batteries. Battery lifetime is the bottleneck of the lifespan of the LEO satellites and is very sensitive to the depth of discharge (DoD), which describes the percentage of energy consumed during discharge relative to the total capacity of the battery. Quantitatively, by carefully designing the routing methods of ISLs, a reduction of 11% - 16% of DoD can be achieved, leading to a doubled battery lifespan [30]. Consequentially, the usage of satellites not being sunlit is to be avoided in order to reduce DoD as much as possible and, in turn, to increase the lifespan of the satellites' batteries.

3.2.3. Satellite Age. LEO satellites have a life span of around 5 years [31] [13], which is very short compared to GEO satellites and terrestrial network infrastructure. Furthermore, LSNs are still in the early stages of development, with more and more satellites being deployed. Updates to both software and hardware of the satellites that could influence their functionalities and performance significantly are still taking place frequently, e.g. the satellites launched for Starlink constellation after September 2023 are equipped with more advanced optical space laser

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hardware than before [32], which is likely to improve the efficiency of ISLs. This being considered, the newer satellites should be favoured in the scheduling of user link.

3.2.4. Exclusion Zones. LEO satellites, as part of the non-geostationary-satellite system (NGSO), shall not cause unacceptable interference to GEO satellite networks, according to Article 22 of the ITU Radio Regulations [33]. As GEO satellites remains above a fixed point of the earth and communicates with the same ground stations, this regulation leads to several exclusion zones for LEO satellites, within which the satellites should reduce radio contact with ground stations or other satellites, in order to keep their Equivalent Power Flux Density (EPFD) under the regulated limitation.

This regulation is currently under controversy. Technical analyses [34], [35] point out that Starlink has likely been violating the EPFD limitations in some exclusion zones, leading to possible interference to specific GEO satellites. On the other hand, there are criticisms [36] that this regulation is outdated, not considering the progresses in the technologies of satellite communication, and reducing the economic benefits of LSNs. However, this opinion is opposed by Bazelon *et al.* [37]. Despite the controversy on the policy, the scheduling algorithm should avoid frequent allocation of links to LEO satellites within the exclusion zones.

3.2.5. Summary. In this subsection, four factors that significantly influence LSNs services are discussed. According to the experiment by Tanveer *et al.* [13], all of these factors are likely considered in the scheduling algorithms of Starlink. The impact of these factors on the goals of the scheduling algorithms mentioned in the previous subsection is complex: each factor can affect multiple design goals, some positively and some negatively. Thus, the design of scheduling algorithms needs to balance the trade-offs of different goals.

Table 2 summarises the overall influence of different factors to be considered in the scheduling algorithm, and their general impact on the goals mentioned in Section 3.1. Positive impacts are indicated with a "+", "-" is for non-favorable impacts.

TABLE 2: The Influence of each Factor on the Goals of Scheduling Algorithms for LSNs

	Higher AoE	**Being Sunlit**	**Newer Satellite**	**Avoid Exclusion Zones**
Latency	+	-	+	-
Capacity		-		-
Coverage				-
Energy	+	+	+	-

The preference for satellites with higher AoE will lead to a lower average distance of user links, and thus brings positive influence on the low latency and energy efficiency goals. The inclination to satellites being sunlit helps to improve energy efficiency, but generally leads to a suboptimal choice towards lower latency and underutilization of total capacity. The favoring for newer satellites can enhance energy efficiency, but it impacts latency in two different directions: on the one hand, it may lead to selecting satellites that are further from the user terminals, thus extending the latency; on the other hand, choosing satellites that equipped with more updated ISL hardware over the older ones allows better utilization of ISLs, thereby reducing latency. The algorithm is responsible to balance these factors and ensure a positive impact on reducing latency overall. In order to avoid radio transmissions within the exclusion zones, satellites on orbits crossing the exclusion zones cannot work full-time during the orbital periods, which leads to negative affections to all of these four goals.

4. Conclusion, Limitations, and Future Work

LSNs, such as Starlink, are providing network services worldwide, especially to ocean and remote areas, where ground-based networks struggle to cover within a reasonable budget. This paper first introduces the current commercial applications of LSNs, including Starlink, OneWeb and Kuiper, highlighting the difficulties and distinction of LSNs' scheduling problem.

Then, in Section 2, the basic composition and topology structure of LSNs are discussed. LSNs can be divided into front- and backhaul. LEO satellite constellations connect to user terminals and ground stations through user and feeder links. The topology structure within satellite constellations differs on whether ISLs are involved, which use laser or radio for direct communication between satellites, improving the transmission efficiency. The topology structure without ISLs is called BP structure, and it has been deployed in commercial LSNs. Currently, ISLs are not yet widely applied, but commercial LSNs like Starlink are paying great attention to them, relative researches and integration are conducted continuously.

Section 3 focuses on fronthaul scheduling. Its objectives and influence factors are analyzed, and summarizes their intertwined relationship, revealing the complexity of designing fronthaul scheduling algorithms. The discussion on fronthaul scheduling in this paper has the following limitations:

- Only ground components and LEO constellations are considered, flying vehicles and GEO satellites as users and relays are not included in the simplified model of the architecture of LSNs. However, studies [38], [39] show that they also have impact on the scheduling for LSNs.
- The application of LSNs as backhaul is not considered. Using LSNs as backhaul of mobile network operators, especially in remote areas, is being considered and studied [40], [41]. If the backhaul services share the same constellations with wideband services, they should be also considered in the scheduling algorithms, to balance the resources between different services.
- Scheduling for backhaul and ISLs is not included. To integrate fronthaul scheduling into the whole scheduling system for LSNs, the cooperation and cross influences of the scheduling for other parts also need to be analyzed.

As for future work, a simple fronthaul scheduling algorithm can be designed based on the concepts of this paper and then tested on simulation platforms such as

Hypatia [42]. The design of algorithms could be improved by taking the situations mentioned in the limitations into consideration with the system.

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