

Optimization of User Equipment Random Access Delay in LEO Satellite Communication Systems via Synchronization Signal Block Periodicity

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Po-Yu Yen

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ABSTRACT

Low Earth Orbit (LEO) satellite network has been a promising technology due to the wide spread coverage area and high data throughput. However, with the high speed of satellites, frequent handover is unavoidable for user equipments (UEs) on the ground, causing significant interruption time and signaling overhead. Thus, we introduce a quasi-earth-fixed satellite beam scheme to solve the continually handover from the UEs at the cell edge. In this scheme, we allocate the satellite beams to the ground cells in order to maximize overall throughput. After that, we also propose a UE cell selection algorithm, which base on both position information and UE measurement.

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CHAPTER 1

INTRODUCTION

Non terrestrial network (NTN) has become a promising technique in next generation network. It provides network connectivity to area that traditional network platform cannot reach. For instance, forests, oceans, and deserts. Various platforms are used to provide network services in NTN, such as GEO, MEO, LEO satellites, UAVs, and drones. Among these platforms, LEO satellites are the most actively discussed. These satellites are located at altitude 500 to 2000 kilometers. The strongest advantage is that they provide global coverage, low latency, and high throughput compared to MEO or GEO satellites.

However, to achieve LEO satellite network service, there are some key challenges that need to be resolved. One of the challenges is the unavoidable frequent handover [1]. The high speed of LEO satellite forces user equipments (UEs) on the ground to switch the serving satellites frequently, as shown in Figure 1. In such scenario, the signalling overhead led by handover signals and the handover interruption time are big issues. 3GPP has discussed some solutions to deal with these issues. By using quasi-earth-fixed cell and satellite switch with re-synchronization [2], the frequent handovers are avoided and the signalling overhead is reduced. For UEs that have already accessed to the network, they can receive the upcoming serving satellite information from the previous one. Also, with the help of the ephemeris data of satellites and the position information of UEs, the matching between satellites and UEs has been largely improved [3]. Nonetheless, for those UEs who have not access to the network, the random access procedure is the only way for them to get into the network. To establish the connection between satellites and UEs, satellites need to transmit synchronization signal block (SSB) to ground for UEs to capture. Once UEs have successfully receive SSBs, the random access procedure starts and the UEs are able to access to the satellite network. Typically in terrestrial network, ground stations send SSB to the serving area every 20 milliseconds. However, the traditional SSB specifications in LEO satellite communication system do not work because the power budget in LEO satellite is so tight that the power is not enough to send all the serving cells in such a short periodicity. Thus, in this thesis we will find out how to deal with this issue by adjust the SSB periodicity and transmitted power.

Cell Diameter Size (km)	UE Speed (km/hr)	Satellite Speed (km/s)	Time to HO (s)
50 (lower bound)	+500	7.56 (NOTE 1)	6.49
	-500		6.74
	+1200		6.33
	- 1200		6.92
	Neglected		6.61
1000 (upper bound)	+500		129.89
	-500		134.75
	+1200		126.69
	- 1200		138.38
	Neglected		132.28

Figure 1: Time to handover for min/max cell diameter and varying UE speed

CHAPTER 2

BACKGROUND AND RELATED WORK

2.1 Random Access Procedure

The random access procedure in 5G is a critical mechanism that allows a User Equipment (UE) to establish initial uplink synchronization and connect to the network (gNB). The procedure is essential for first-time access, handovers, and re-establishing connections after inactivity or loss of synchronization. Here are some typical steps in contention-based random access:

- Preamble Transmission (Msg1): The UE randomly selects a PRACH (Physical Random Access Channel) preamble and transmits it to the gNB. This "signature" indicates the UE's request for network access.
- Random Access Response (Msg2): The gNB detects the preamble and responds with a Random Access Response (RAR), which includes timing adjustment, a temporary identity, and an uplink resource grant. This enables the UE to align its timing with the network and prepare for further communication.
- RRC Connection Request (Msg3): Using the granted resources, the UE sends a connection request, which includes its identity and the reason for establishing the connection, such as initial access or handover.
- Contention Resolution (Msg4): The gNB sends a contention resolution message confirming which UE has successfully completed the random access. If multiple UEs used the same preamble, only the correct one will be acknowledged, resolving the contention.

2.2 Synchronization Signal Block

2.2.1 Components of SSB

The Synchronization Signal Block (SSB) in 5G New Radio (NR) is a critical structure for initial access between the user equipment (UE) and the base station (gNB). Each SSB is composed of three main elements:

- Primary Synchronization Signal (PSS): The PSS enables the UE to obtain symbol timing and perform coarse frequency synchronization. It allows the

UE to find the starting point of a radio frame and resolves the physical layer cell identity group.

- Secondary Synchronization Signal (SSS): The SSS complements PSS by providing additional information to finalize the cell identification and determines the frame timing, which refines synchronization accuracy for the UE.
- Physical Broadcast Channel (PBCH): The PBCH conveys essential cell-specific information, including system configuration parameters (such as the System Frame Number), which the UE needs for further connection setup after synchronization.

These components jointly allow the UE to perform downlink synchronization, cell identification, and to decode key system information for network access.

2.2.2 SSB Configuration

A series of SSBs called *SSB burst* are sent in a half frame (5ms), the number of SSBs in a SSB burst is determined depends on the carrier frequency and the subcarrier spacing of the transmitted signals. Each cell has a SSB periodicity, defined as the time interval the SSB burst be transmitted to the cell, as shown in Figure 2.

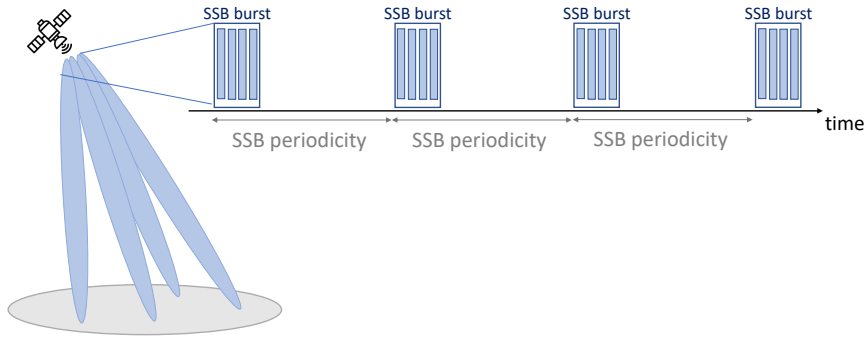


Figure 2: Illustration of SSB configuration.

2.2.3 SSB in LEO Satellite Network

In terrestrial network (TN), the base station (gNB) transmits SSBs periodically in time and across different spatial directions through beam sweeping, enabling the UE to detect the best SSB and select the optimal beam for communication. In NTN, the SSBs have the same function but the coverage area of each satellite is much bigger than TN, which means each satellite has to provide service to more cells. Moreover, the long distance from satellite to ground and the power budget

of each satellite forces us to properly allocate the power of the SSB. Thus, it is essential for us to manage the SSB transmitted power and the periodicity of each cell.

2.3 Related Work

CHAPTER 3

SYSTEM MODEL

3.1 System Overview

This chapter introduces the LEO satellite communication system, as illustrated in Figure 3. We consider one of the satellites in the LEO satellite communication system. It consists of M beams, represented by $\mathcal{M} = \{m \mid m = 1, 2, \dots, M\}$. In the coverage area of the satellite, it contains K cells, indexed by $\mathcal{K} = \{k \mid k = 1, 2, \dots, K\}$. To achieve optimal coverage and minimize overlap, all ground cells are arranged in a regular hexagonal grid, ensuring uniform cell size. There are U user equipments (UEs) in the coverage area, indexed by $\mathcal{U} = \{u \mid u = 1, 2, \dots, U\}$.

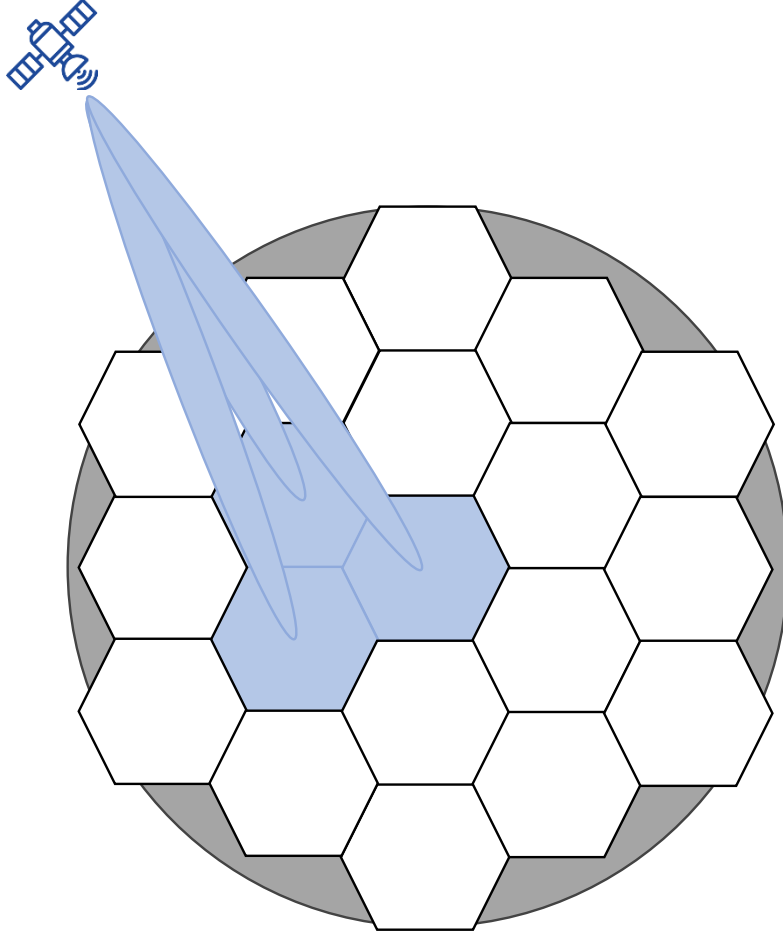


Figure 3: Illustration of satellite beams and cells.

We define a short time T^{slot} as the time duration of a time slot, and T^{total} as the total time that the satellite serves the area. Thus, there are T^{total}/T^{slot} time

slots in total service time, denoted as $\mathcal{T} = \{t \mid t = 1, 2, \dots, T^{total}/T^{slot}\}$.

In this thesis, we adopt the quasi-earth-fixed scheme. Unlike the earth-moving cell scheme—where the coverage areas of satellite beams move as the LEO satellites orbit—this approach directs satellite beams so that each beam consistently covers the same geographical cell for a given period. Thus, the coverage area of each satellite beam remains fixed relative to the ground during that interval. Throughout, we assume each satellite beam is oriented toward the center of its designated cell.

We define a power budget for the satellite. Let $P_m[t]$ denote the transmitted power of the m -th beam from the satellite at time slot t . The aggregate transmit power of all beams on the satellite must satisfy:

$$\sum_m P_m[t] \leq P^{total}, \quad \forall t \in \mathcal{T} \quad (3.1)$$

where P^{total} is the maximum transmit power per satellite.

The locations of UEs wishing to access the network are assigned randomly within their corresponding cells, and the population of each cell are generated according to area population density statistics.

3.2 Channel Model

3.2.1 Free Space Path Loss

In the LEO satellite system, the free space path loss from the satellite to cell k is expressed as follows [4]:

$$L_k = \left(\frac{\lambda}{4\pi d_k} \right)^2 \quad (3.2)$$

where λ is the wavelength, and d_k is the distance between the satellite and the center of the k -th cell.

3.2.2 Shadowed-Rician Fading Channel

The shadowed-Rician fading model is suitable for satellite communication systems because it accurately reflects the physical propagation environment, capturing both the presence of a strong line-of-sight (LoS) signal and the effects of shadowing from obstacles [5]. Let h_k denote the channel gain between the satellite and the k -th cell. The cumulative distribution function (CDF) of the channel gain is:

$$F_{h_k}(x) = K \sum_{n=0}^{\infty} \frac{(m)_n \delta^n (2b)^{1+n}}{(n!)^2} \gamma \left(1 + n, \frac{x}{2b} \right) \quad (3.3)$$

where $K = (\frac{2bm}{2bm+\Omega})^m / 2b$, $\delta = \Omega / (2bm + \Omega) / 2b$, Ω is the average power of the LoS component, $2b$ is the average power of the multipath component except the LoS component, and m is the Nakagami parameter.

3.2.3 Antenna Radiation Pattern

We introduce the antenna radiation pattern in [6]:

$$G(\theta_{m,u}) = G_{max} \left[\frac{J_1(\mu(\theta_{m,u}))}{2\mu(\theta_{m,u})} + 36 \frac{J_3(\mu(\theta_{m,u}))}{\mu(\theta_{m,u})^3} \right]^2 \quad (3.4)$$

where $\theta_{m,u}$ is the boresight angle between the user position and the beam center with respect to the satellite, G_{max} is the maximum antenna gain, $\mu(\theta)$ is defined as $2.07123 \cdot \sin(\theta) / \sin(\theta_{3dB})$, θ_{3dB} is the 3 dB half-power beamwidth angle of the antenna, and $J_1(\cdot)$, $J_3(\cdot)$ are the Bessel functions of the first kind of orders 1 and 3, respectively.

With the transmitted power P_m from the m -th beam of the satellite, the received power at the u -th user, $\hat{P}_{m,u}$, is given by:

$$\hat{P}_{m,u} = P_m \cdot L_k \cdot h_k \cdot G(\theta_{m,u}) \quad (3.5)$$

where k is the cell where user u is located.

3.3 Synchronization Signal Block Model

During each time slot, the satellite beams transmit one SSB burst to ground cells, and each SSB burst contains at most M SSBs. In this thesis, we adjust the SSB periodicity of each cell due to two main reasons. First, the elevation angle of the satellite changes during the service time. The smaller elevation angle it is, the more power each beam has to allocate to achieve the successful transmission. Therefore, it is essential to adjust SSB periodicity to meet the power budget requirement. Second, we adjust the SSB periodicity based on the previous UE random access delay performance. Thus, we define 1 epoch equals to N time slots, and we adjust the SSB periodicity every epoch. We denote the epochs in the service time as $\mathcal{S} = \{s \mid s = 1, 2, \dots, (T^{total}/T^{slot})/N\}$. During each epoch, the SSB periodicity of each cell is fixed. We then define the SSB periodicity of the cell k at the s -th epoch as the number of slots between two consecutive SSBs that transmit to the k -th cell, denoted as $T_k^{SSB}[s]$.

3.4 UE Random Access Delay

The random access delay $T_u[s]$ for the u -th UE is a random variable, defined as the time duration between the start of SSB measurement and the successful

reception of SSB at the s -th epoch, as shown in Figure ?? . T_u can be decomposed into two parts: $T_u^i[s]$ (initial waiting time at the s -th epoch) and $T_u^l[s]$ (additional delay due to failed attempts at the s -th epoch). $T_u^i[s]$ is a random variable that represents the time from the start of SSB measurement to the arrival of the first SSB, and $T_u^l[s]$ is another random variable that represents the time from the first SSB arrival to the successful SSB reception. Since the UE can start SSB measurement at any time, $T_u^i[s]$ is a uniformly distributed random variable $U(0, T_k^{SSB}[s])$. $T_u^l[s]$ is a multiple of $T_k^{SSB}[s]$, depending on the number of failures $Q_u[s]$. If the received SSB power $\hat{P}_{m,u}[t]$ is less than the threshold P^{th} , the UE fails to measure SSB. The probability that the received SSB power is less than P^{th} is denoted as $R_u[t]$. The mathematical formulation is as follows:

$$T_u[s] = T_u^i[s] + T_u^l[s] \quad (3.6)$$

$$F_{T_u^i[s]}(x) = \begin{cases} \frac{x}{T_k^{SSB}[s]}, & 0 \leq x < T_k^{SSB}[s] \\ 1, & x \geq T_k^{SSB}[s] \\ 0, & \text{otherwise} \end{cases} \quad (3.7)$$

$$T_u^l[s] = Q_u[s] \cdot T_k^{SSB}[s] \quad (3.8)$$

$$\Pr\{Q_u[s] = n\} = (1 - R_u[(s-1) \cdot N + n]) \prod_{i=1}^{n-1} R_u[i] \quad (3.9)$$

where k_u is the cell where the u -th UE is located, and $F_{T_u^i}(x)$ is the CDF of T_u^i . R_u can be expressed by F_{h_k} as follows:

$$\begin{aligned} R_u[t] &= \Pr\{\hat{P}_{m,u}[t] < P^{th}\} \\ &= \Pr\{h_k < \frac{P^{th}}{P_m[t] \cdot L_k \cdot G(\theta_{m,u})}\} \\ &= F_{h_k}(\frac{P^{th}}{P_m[t] \cdot L_k \cdot G(\theta_{m,u})}) \end{aligned} \quad (3.10)$$

3.5 Problem Formulation

This section formulates the optimization problem based on recent 3GPP standardization discussions. In the 3GPP RAN1 #116 meeting [7], further specifications for the LEO satellite communication scenario were defined. The main challenge is to provide random access to a large number of cells with limited satellite power. Extending the SSB periodicity for some cells reduces satellite power consumption but increases UE random access delay. The transmitted SSB power also affects the success probability of the random access procedure. The trade-off among power allocation, SSB periodicity, and UE random access delay is modeled as follows:

$$\begin{aligned}
& \min_{P_m[t], T_k^{SSB}[s]} \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}} T_u[s] \\
& \text{subject to} \\
& \sum_m P_m[t] \leq P^{total}, \quad \forall t \in \mathcal{T} \\
& P_m[t] \geq 0, \quad \forall m \in \mathcal{M}, t \in \mathcal{T} \\
& T_k^{SSB}[s] \leq N, \quad \forall k \in \mathcal{K}, \forall s \in \mathcal{S} \\
& T_k^{SSB}[s] \in \mathbb{N}^+, \quad \forall k \in \mathcal{K}, \forall s \in \mathcal{S}
\end{aligned} \tag{3.11}$$

where \mathbb{N}^+ is the set with all positive integers.

CHAPTER 4

PROPOSED ALGORITHM

CHAPTER 5

PERFORMANCE EVALUATION

All figures should be of the same width whenever possible for consistency.

5.1 Simulation Setup

We use BONMON [?] to solve the optimization problem. The simulation setup follows that in [?].

5.2 Simulation Results

CHAPTER 6

CONCLUSION AND FUTURE WORK

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