地球同步軌道衛星之波束管理
Beam Management in GEO Satellite System

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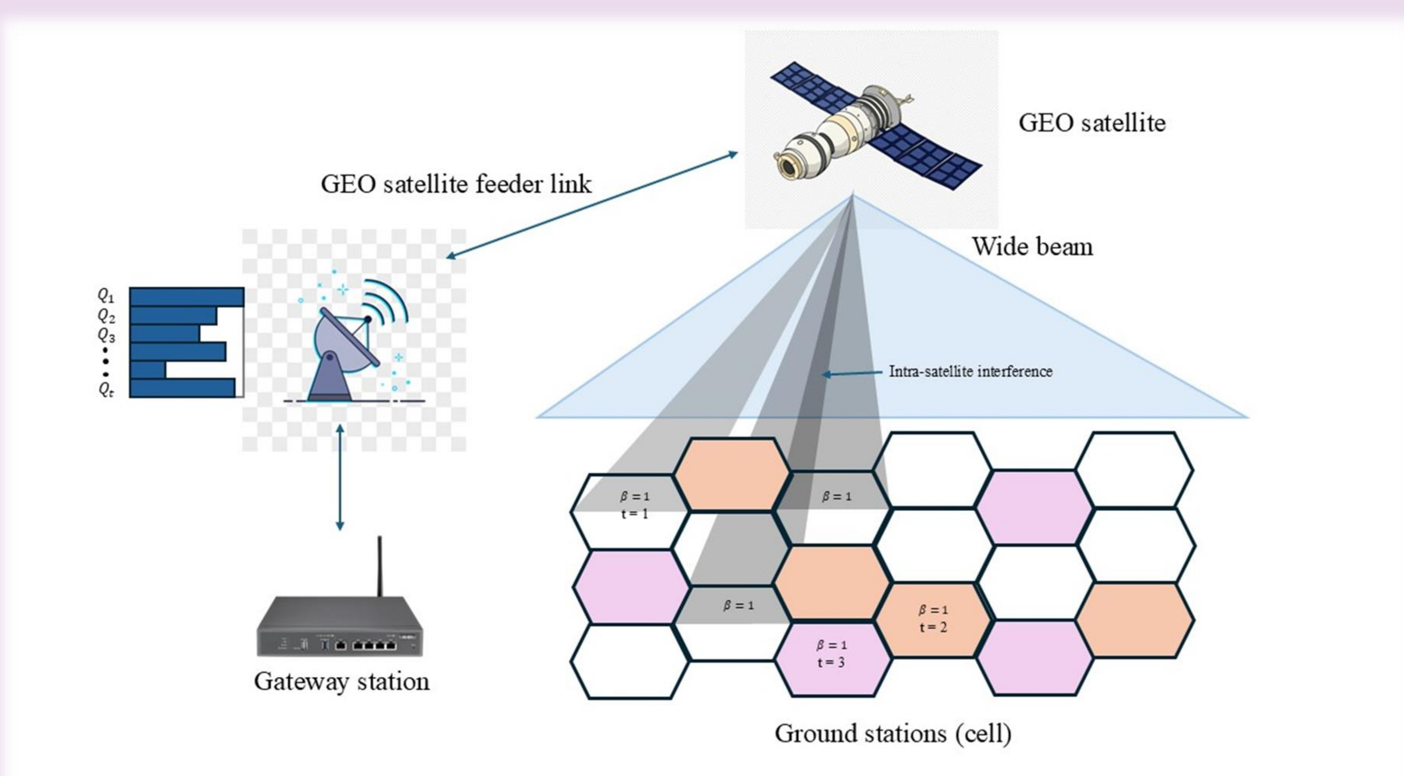
Abstract

The Multi-Beam Satellite (MBS) combined with Beam Hopping technology enables flexible allocation of satellite resources to address the uneven distribution of ground demand. It achieves an effect similar with TDMA by staggering the service times of adjacent areas, reducing mutual interference and improving satellite utilization efficiency. Therefore, the objective of this research is to design an appropriate beam pattern to allocate satellite beams effectively across different regions and time slots, thereby maximizing transmission capacity.

Additionally, to address system stability concerns, this study aims to prevent demand accumulation (queue backlog) caused by the inability of satellite services to meet user demand. We employ Lyapunov optimization to develop an algorithm that balances system performance and stability. Furthermore, we integrate a greedy algorithm to design the Beam Hopping pattern, achieving stable and efficient satellite communication services.

System Model



Time is divided into T time slots, and for each time slot, a unique Beam Hopping (BH) pattern is designed (as illustrated by different colors in the diagram, each representing a BH pattern for a specific time slot). In each time slot, the optimal illumination scheme is determined. Ground stations selected for illumination are denoted as β=1, while those not selected are denoted as β=0. Furthermore, the total number of simultaneously illuminated ground stations must not exceed the satellite's beam limit K.

Problem Formulation & Decomposition

The goal of our algorithm is to satisfy as much demand as possible over the long term, specifically the total demand for each ground station while adhering to the following constraints:

1. The total number of illuminated ground stations cannot exceed the satellite's beam limit.
2. βis a binary variable, where 1β=1 indicates the ground station is illuminated, and β=0 indicates it is not.
3. The actual allocated demand$D_n(t)$ must lie between 0 and the ideal demand $A_n(t)$. i. e. , $0 \le D_n(t) \le A_n(t)$.

4. The long-term expected average of the queue backlog must remain finite, ensuring system stability.

C1: $\sum_{n=1}^{N} \beta_n(t) \le K$ C3: $0 \le D_n(t) \le A_n(t)$

C2: $\beta_n(t) \in \{0,1\}$ C4: $\lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T}\sum_{n=1}^{N} E[Q_n(t)] < \infty$

Then use Lyapunov optimization to deal with constraint C4 :

Lyapunov function: $L(Q(t)) = \frac{1}{2}\sum_{n=1}^{N} Q_n^2(t)$

Lyapunov drift: $\Delta Q(t) = E\{L(Q(t+1)) - L(Q(t)) \mid Q(t)\}$

Lyapunov Optimization uses the Lyapunov drift to represent system stability. When the Lyapunov ΔQ is smaller, it indicates that the accumulated queue backlog Q_n is reduced. Over the long term, this leads the system toward stability.

The complicated functions can be decomposed into:

$\mathbf{P_1}:\quad \min_{D_n(t),v_n,t} \sum_{n=1}^{N} D_n(t+1)(Q_n(t) - V), \quad C_3: 0 \le D_n(t) \le A_n(t)$

The optimal solution of $\mathbf{P_1}$:

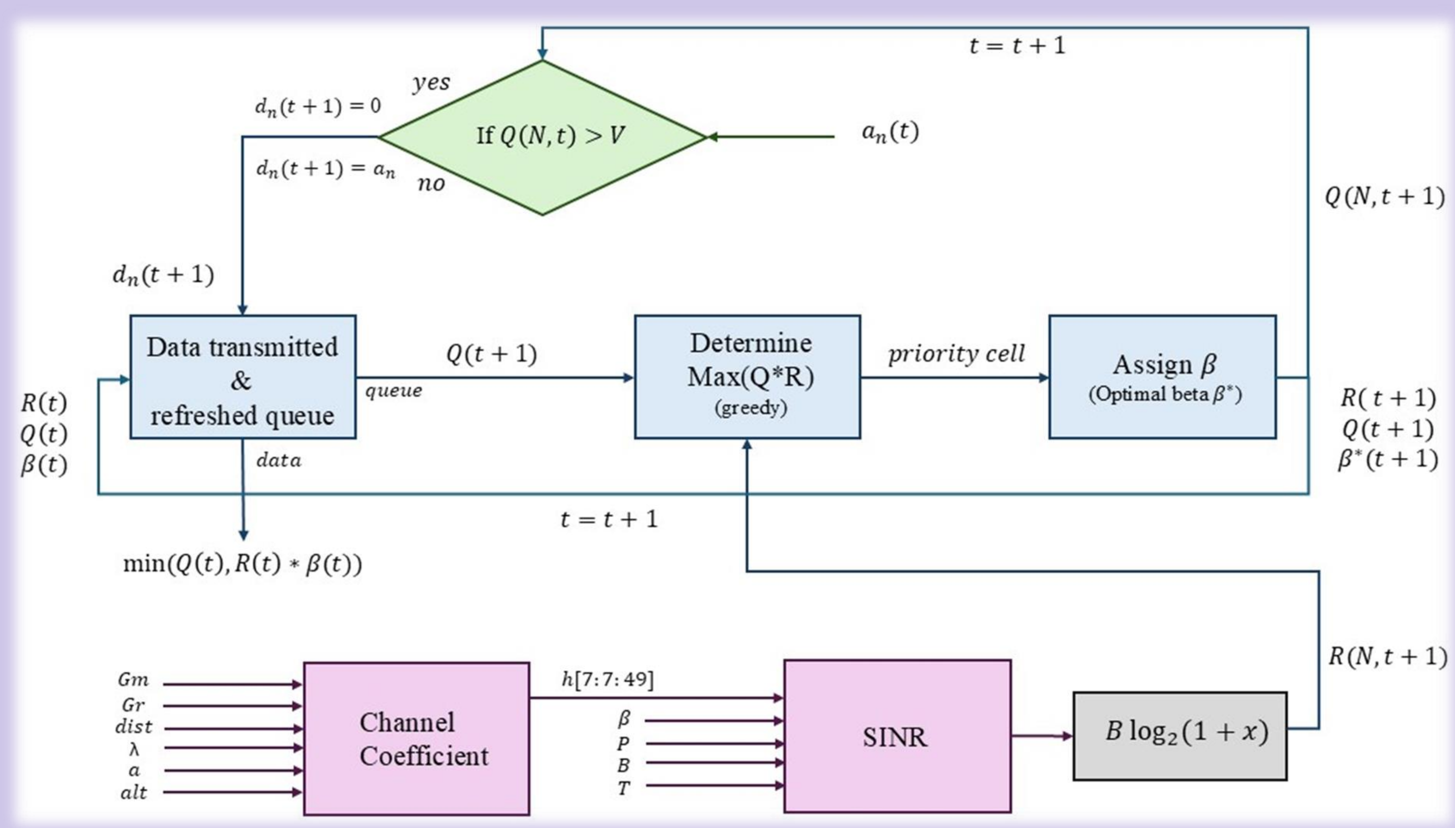
$$D_n^*(t+1) = \begin{cases} 0, & Q_n(t) \ge V \\ A_n(t+1), & Q_n(t) < V \end{cases}$$

$\mathbf{P_2}:\quad \max_{\beta_n(t),\forall n,t} \sum_{n=1}^{N} Q_n(t) R_n(\beta_n(t))$

$$C_1: \sum_{n=1}^{N} \beta_n(t) < K$$

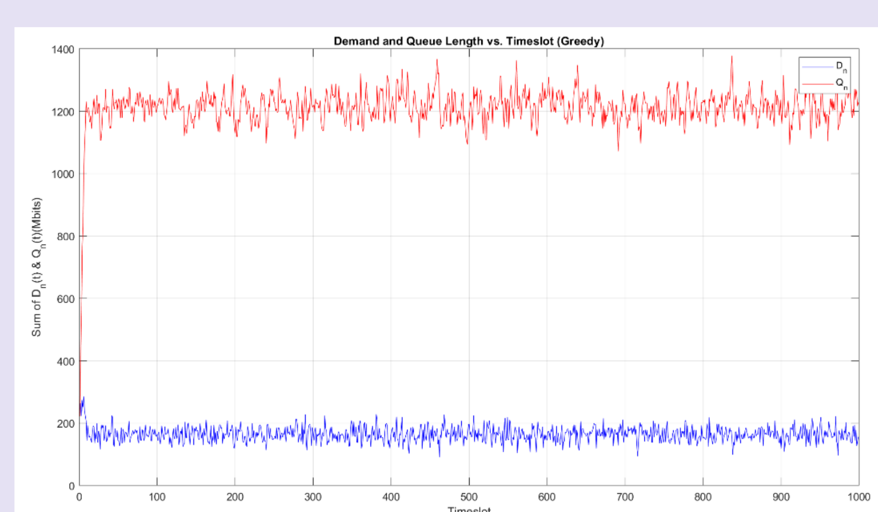
$$C_2: \beta_n(t) \in \{0,1\}$$

Algorithm

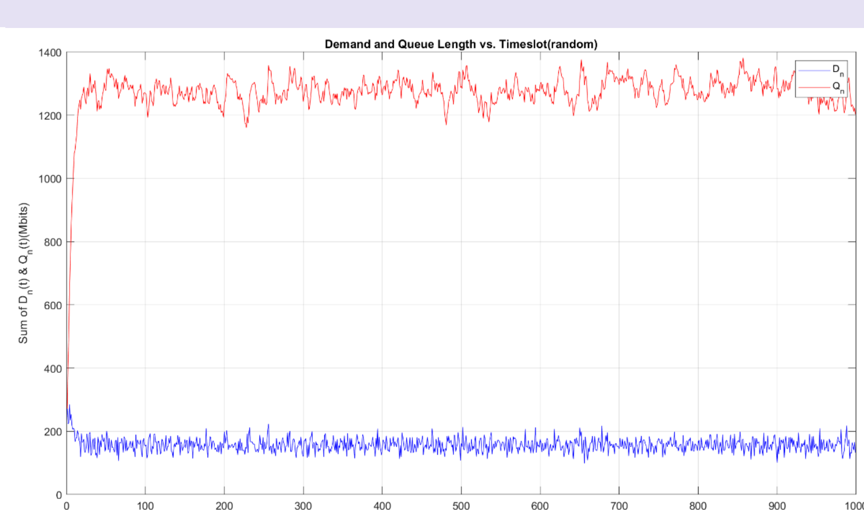


Designed greedy algorithm

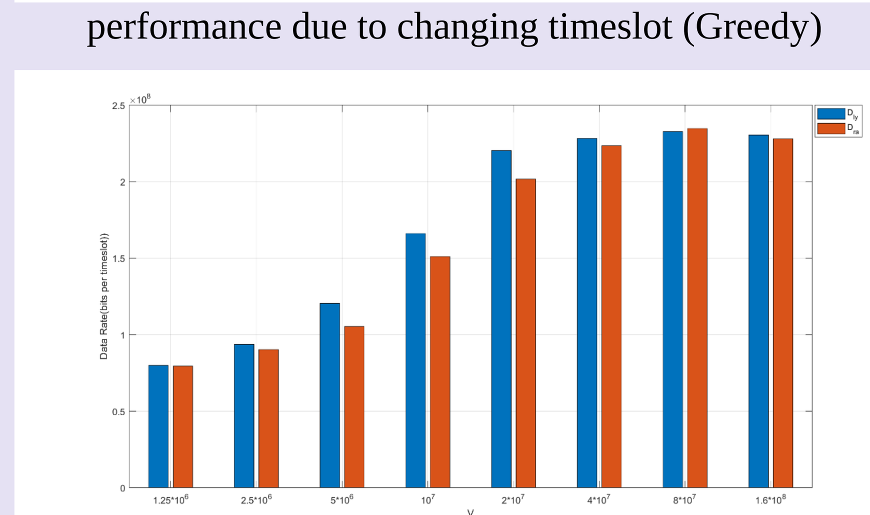
Simulation Result



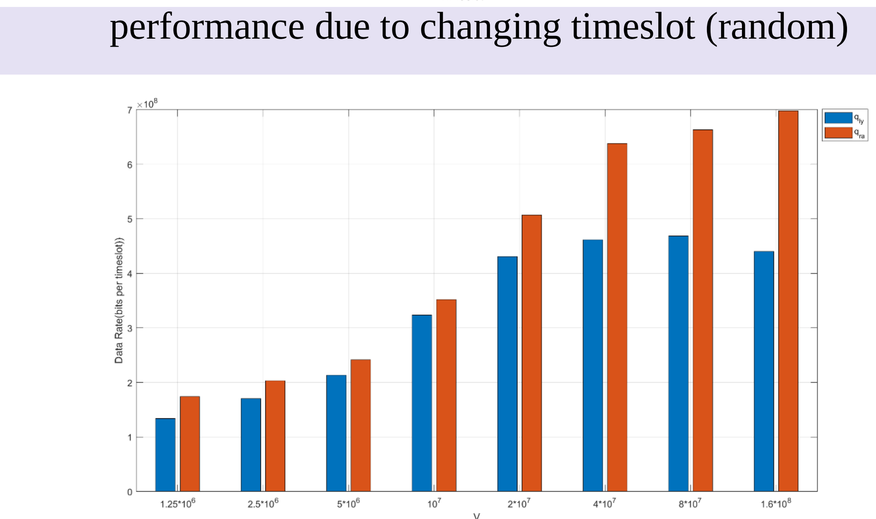
performance due to changing timeslot (Greedy)



performance due to changing timeslot (random)



Data demand due to changing Lyapunov Control Parameter



queue length due to changing Lyapunov Control Parameter

Compared with random Beta, since Lyapunov Optimization has larger demand and smaller queue length during simulation, the performance is better.

Conclusion

In this project, we employed an effective method to improve satellite utilization efficiency during beam allocation. In the future, we will attempt to apply this method to multiple low-Earth orbit satellites or other types of communications. Additionally, we will explore the implementation of more feasible algorithms.