Optimal Content Placement Based on Popularity at Low Earth Orbit Satellites

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***Abstract*—Low Earth orbit (LEO) satellite networks, orbiting below 2,000 km, have attracted attention for providing Internet to regions lacking infrastructure. Their lower altitude enables low-power, low-latency, high-capacity communications. However, low uplink throughput poses a bottleneck when transmitting large volumes of data from ground stations to satellites, leading to increased latency. Many studies are currently investigating LEO satellite caches as a solution to this problem. LEO satellites orbit the earth at high speed and receive delivery requests from various regions of the world. Thus, an effective caching strategy is required to maximize the limited cache capacity while considering the global popularity of content. In this paper, we propose an optimal content placement method for LEO satellite caches that takes into account the popularity of content.**

I. Introduction

In recent years, with the spread of mobile communication devices, users' demands for anytime, anywhere network access have been increasing. However, Internet access is primarily dependent on terrestrial infrastructure, which is often impractical to deploy in remote areas such as deserts, oceans, and mountainous regions due to high costs and low expected returns. As a result, over 3 billion people worldwide lack Internet access, with more than 1 billion residing in areas with no connectivity [1].

LEO satellite networks complement terrestrial networks and help bridge the digital divide. They also serve as an alternative when terrestrial infrastructure is damaged. LEO satellite networks consist of satellites orbiting at altitudes between 350 km and 2,000 km, acting as relay nodes. LEO satellites are closer to the earth's surface, resulting in shorter access latency, less power consumption for signal transmission to the satellite, and greater communication capacity. However, LEO satellites move at high speeds and the coverage by individual satellites is relatively limited, so a large constellation of satellites is needed to provide services to the entire earth [2].

One of the challenges of current LEO satellite networks is low uplink throughput. The uplink throughput from a ground-based server to a ground terminal is a bottleneck when delivering large-volume content from a ground-based server to a ground terminal via a LEO satellite. As a solution to this problem, a LEO satellite cache is being considered [3] [4]. Caching content on LEO satellites allows direct content delivery, reducing both uplink usage frequency and delivery delay.

Since LEO satellites orbit the earth at high speed, they receive delivery requests from various regions of the world. Therefore, caching more globally popular content in the cache on the LEO satellite will improve the overall cache hit ratio. In addition, considering inter-satellite communication technology [5] that enables optical communication between LEO satellites, if the target content is not cached on the destination satellite, it can be delivered using inter-satellite communication. In this case, since the number of inter-satellite communications affects the delay time required for delivery, the same content should be distributed over multiple LEO satellite caches to reduce the number of hops required for delivery.

In this paper, we propose a content placement method on LEO satellites that improves the average cache hit ratio and reduces the number of hops required for delivery by designing the number of placements of each content on LEO satellites, taking into account the global popularity of the content. In addition, we propose a method to optimize the content placement considering the capacity of the LEO cache in the proposed placement method.

II. Proposed method

This study proposes a content placement method for satellite caches based on two key principles. The first is to improve the overall cache hit ratio by placing a large number of highly popular content, and the second is to reduce the number of delivery hops by distributing the same content instead of consolidating it. We propose a scheme where content is distributed at equal intervals, adjusted by popularity.

We define a placement interval for each content m. The placement interval in the longitude direction is x_m, and one content is placed for every x_m orbits. Similarly, the latitudinal placement interval, denoted as y_m, specifies that one content is placed every y_m satellites within the same orbit.

III. Optimization methods

In this paper, we optimize the placement interval for each content in the proposed method with the aim of maximizing the average cache hit ratio. Two optimization methods, genetic algorithm (GA) [6] [7] and greedy method, are used for comparison.

In the GA approach, the estimated cache hit ratio for each content is given by $1/(x_m y_m)$. F, the overall fitness function in GA is determined by summing the estimated cache hit ratios for all contents, weighted by their respective request ratios q_m.

That is, F is given by

$$F = \sum_{j=1}^{M} \frac{q_m}{x_m y_m}, \qquad (1)$$

where M is the number of contents, and q_m is the request ratio for content m. The values of x_m and y_m are optimized to maximize this fitness function. When calculating the adaptability, a decision is made regarding the cache capacity constraints. The total number of contents to be placed is calculated from the placement interval of each content, and if the total number exceeds the total cache capacity of all satellites, a penalty is added to reduce the degree of adaptation. This process takes into account the satellite's cache capacity constraints.

In the greedy method, the placement interval is set to unity in order from the most popular content until the cache capacity is exceeded, and when the capacity is exceeded, the placement interval is expanded.

IV. Numerical Evaluation

The content placement strategies optimized using GA and the greedy method are evaluated through a simplified computer simulation, assuming a static grid-like satellite arrangement without considering satellite mobility. The number of orbits and satellites per orbit were configured based on OneWeb's polar orbit constellation. The number of orbits is 12, and the number of satellites in each orbit is 49. All satellites hold a cache, and the capacity of each satellite cache is 10 contents. There are 1,000 contents in total, and we assume the Zipf distribution for q_m. The assumed LEO satellite network covers the entire earth, and each delivery request is always sent to one of the satellites. Content placement is based on the placement spacing optimized by each method. First, all contents are placed one by one on random satellites, and then the contents are placed according to the optimized placement intervals. For each content, one satellite is randomly selected to start placement, and the contents are placed according to the placement interval at equal intervals starting from the selected satellite.

Each simulation was run 10 times, and the results were averaged for evaluation. Figure 1 shows the average cache hit ratio when the bias of the Zipf distribution is changed. The cache hit ratio is high for the greedy method of placement, followed by the cache hit ratio for the GA placement.

Figure 2 shows the average number of hops when the parameter representing the bias of the Zipf distribution is varied. The number of hops is slightly reduced in the optimization by GA compared to the optimal placement by the greedy method. This is because the placement by GA tends to place more contents with medium popularity than the placement by the greedy method.

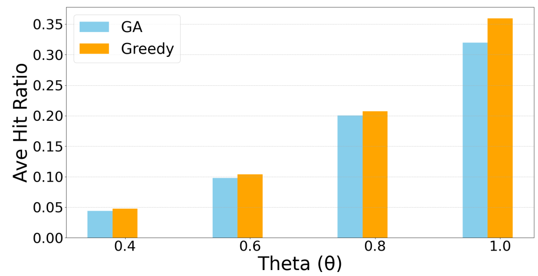

Fig. 1. Average cache hit ratio against Zipf parameter of content popularity

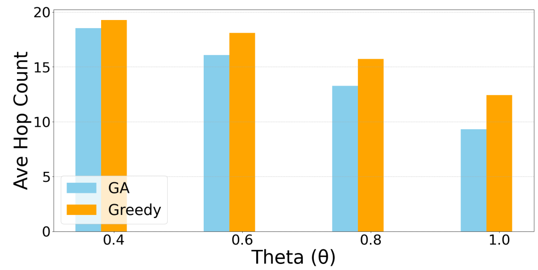

Fig. 2. Average hop length against Zipf parameter of content popularity

V. Summary

In this paper, we proposed a caching scheme for LEO satellite networks to address low uplink throughput by distributing content at equal intervals. The placement interval was optimized using GA and the greedy method, and performance was evaluated based on cache hit ratio and hop length. Future work includes using a more realistic simulator and incorporating hop count evaluation into GA's adaptability.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number 23K21664, 23K21665, and 23K28078.

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