A Two-layer Caching Model for Content Delivery Services in Satellite-terrestrial Networks

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***Abstract*—With the development of satellite communication technologies and user requirements for pervasive network access, there is a trend to integrate satellites into the terrestrial network infrastructure. Such kind of satellite-terrestrial network is often used for content delivery services as satellites are with wide-area coverage. In terrestrial networks such as Internet, in-network caching has been proved to be an effective method to improve the network performance in terms of throughput and delay. Based on this observation, we involve caches in the satellite-terrestrial networks. Particularly, a two-layer caching model is proposed for content delivery, where caches placed in the ground stations constitute the first caching layer and caches deployed in the satellite forms the second one. On the satellite, to make full use of the broadcast advantage, we set a window to aggregate the requests for the same files from ground stations. These requests will be served by one satellite broadcasting when the aggregation window expires. Our goal is to minimize the downlink and uplink satellite bandwidth consumption, which requires joint caching optimization between the satellite and ground stations. We formulate the joint caching optimization problem as a nonlinear integer programming problem. Furthermore, a caching strategy based on the genetic algorithm is proposed to solve the problem efficiently. The simulation results show that the proposed caching strategy significantly outperforms content popularity based and random caching strategies in terms of satellite bandwidth consumption.**

***Index Terms*—Satellite-terrestrial Networks, Content Delivery, Caching**

I. Introduction

In recent years, the popularization of mobile communication devices, such as smartphones and tablet PCs, makes user requirements for pervasive network access at anytime and anywhere become more intense. However, current network infrastructures for user access are mainly made up of terrestrial devices, which are prone to be damaged in the disasters. In addition, it is inconvenient to deploy network infrastructures in the remote and isolated areas such as desserts, seas and mountains. With the development of satellite communication technologies, there is a trend to integrate satellites into the terrestrial network infrastructure [1] [2]. Such kind of the satellite-terrestrial network will become an essential part of future Internet. Many Internet companies including Google, Facebook have launched or plan to launch their own satellites for Internet access. Particularly, as satellites can provide wide-area coverage, satellite-terrestrial networks have a potential to be widely used for content delivery services.

In terrestrial networks such as Internet, in-network caching has been proved to be an effective method to improve the network performance in terms of throughput and delay. In order to implement in-network caching in Internet, Information-Centric Networking (ICN) has drawn considerable attention from academic community [3] [4]. ICN is characterized by two major features: routing-by-name and in-network caching. The former means that a specific content can be retrieved from the network by its name without the host identification, while the latter indicates that each network element (e.g., router) is equipped with storage of certain size and able to cache the data. Moreover, due to caches are distributed among network elements, finding the optimal caching strategy has become an important research issue in ICN.

In-network caching can also be used to improve the performance of satellite-terrestrial networks. There exists some work on this issue. The critical characteristics of the ICN architecture and their effects on satellite-terrestrial networks were analyzed in [5]. Literature [6] proposed a caching scheme based on the interest profile of users to improve resource efficiency of satellite communication. In [7], an ICN architecture is introduced to three satellite-terrestrial network scenarios to overcome the high propagation disadvantage of satellite networks.

However, the aforementioned work mainly focuses on caching in terrestrial networks, neglecting the role of caching in satellites. In fact, terrestrial storage capacity is limited even unavailable in many cases such as network scenarios for sailors on board of a ship and researchers carrying on field investigation. On the other hand, with more advanced on-board processing and larger storage capacity, satellites have become more powerful than before [1] [8]. In this context, considering the wide coverage and broadcast advantages of satellites, it is necessary and practical to cache parts of data flowing at satellites, especially for content delivery services.

In this paper, we equip the satellite as well as ground stations in terrestrial networks with caches to reduce satellite bandwidth consumption for content delivery services. A two-layer caching model is proposed in satellite-terrestrial networks where caches placed in the ground stations constitute the first caching layer and cache deployed in the satellite forms the second one. Intuitively, caches at each ground station are used for the popular content in its local area, while the satellite caches are used for the most popular content in its whole coverage. Theoretically, we can see that joint caching optimization between the satellite and ground stations are required to minimize satellite bandwidth consumption. Be-

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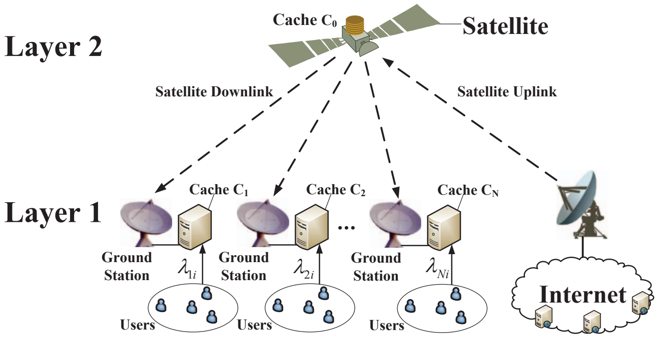

Fig. 1. Satellite-terrestrial networks architecture with a two-layer caching model

sides, the broadcast advantage of the satellite can be exploited to further reduce satellite bandwidth consumption. The main contributions are described as follows.

1) We propose a two-layer caching model in satellite-terrestrial networks for content delivery services. Both the satellite and ground stations are equipped with caches. Specifically, caches placed in ground stations constitute the first caching layer and caches deployed in the satellite form the second one. The satellite can involve caches to achieve significant performance improvement for its wide-area broadcasting capability.
2) In order to take the broadcast advantage of the satellite, a window is set to aggregate requests from ground stations on the satellite. All the aggregated requests can be served by one satellite broadcasting when the aggregation window expires. The duration of the aggregation window is carefully considered to leverage caching efficiency and content delivery delay.
3) Joint caching optimization between the satellite and ground stations is required to minimize satellite bandwidth consumption. We formulate such kind of joint caching optimization problem as a NonLinear Integer Programming (NLIP) problem. Furthermore, a caching strategy based on the genetic algorithm is proposed to solve the problem efficiently.

The rest of the paper is organized as follows. In Section II we describe the proposed two-layer caching model and file popularity model for content delivery. Then, in Section III, the joint caching optimization problem is formulated and the proposed caching strategy based on the genetic algorithm is described. Numerical results are shown in Section IV. At last, conclusions are drawn in Section V.

II. System Model

In this paper, content delivery services are considered in the satellite-terrestrial network. As shown in Fig.1, content in forms of files originated from a server in Internet and sent to users are relayed by the satellite and ground stations. Firstly, we propose a two-layer caching model and find that the optimal caching strategy in the proposed model is a joint caching optimization problem between the satellite and ground stations. Furthermore, on the satellite, a window is proposed to aggregate the requests for the same content from the ground stations so that the broadcast advantage of the satellite can be fully exploited. In order to reflect the users' preference for different files, the file popularity is modeled by a Zipf-like distribution. Finally, we use time-varied functions to describe the uplink and downlink satellite bandwidth based on the Rice channel model

A. A Two-layer Caching Model

The proposed two-layer caching model in the satellite-terrestrial network is shown in Fig.1. The satellite-terrestrial network is composed of four components: one gateway on the ground connected to Internet, one satellite, several ground stations and user nodes. Both ground stations and the satellite are equipped with caches. Then all the caches of ground stations and the satellite naturally form a two-layer caching architecture. In the proposed two-layer caching model, the satellite determines the caching locations of the files, based on the request distribution. Then, the satellite marks the files that the ground stations should cache and delivers them to the corresponding ground stations. We let S_n represent the size of cache in the n-th ground station and S_0 for the satellite. The caches in ground stations constituting the first caching layer are denoted by a set $\mathcal{C}$, and we have $\mathcal{C} = \{C_1, C_2 \cdots C_N\}$. The second caching layer is constituted by one cache C_0 in the satellite.

In traditional satellite-terrestrial networks, only ground stations are assumed to have caching capability. Each ground station caches the most popular files in its local area to satisfy local users' demand. But in the proposed two-layer caching architecture, the additional satellite cache makes the optimal caching strategy become a joint caching optimization problem between the satellite and ground stations. We can not simply cache the most popular files in each ground station or the satellite to achieve the best network performance. More sophisticated caching strategies are required.

In order to take full advantage of the broadcast nature of the satellite, a window is set at the satellite to aggregate all requests from the ground stations. In this case, the requests which are not answered by the ground stations are aggregated at the satellite during one window time. Then the satellite serves all the requests for the same files by one broadcasting at the end of aggregation window. By doing so, satellite bandwidth consumption can be further reduced in the uplink and downlink directions.

The file delivery procedure is described as following: when a user sends a request for a file, the ground station will search its local cache for the corresponding file. If the ground station already caches the file, it will respond to the request directly. Otherwise, the request will be sent to the satellite. If the corresponding file is already cached in the satellite, the satellite will broadcast this file to all ground stations after an aggregation window. But if the cache miss occurs again in the satellite, the request will be forwarded to the gateway on the

TABLE I
NOTATIONS

Symbol	Description
$\mathcal{C}$	Set of caches in ground stations
$\mathcal{F}$	Set of files
C_n	Cache in the n-th ground station, $n \in \{1, 2...N\}$
C_0	Cache in the satellite
S_n	Cache size of C_n
S_0	Cache size of the satellite
s_i	Size of the i-th file
λ_n	Average demand at C_n
λ_{ni}	Average demand at C_n for the i-th file
λ_{0i}	Average demand at the satellite for the i-th file
p_{ni}	Popularity for the i-th file at C_n
p_i	Request probability for the i-th file at the satellite within τ
τ	Aggregation window for multicast
ω	A weight factor denoting the importance of downlink
x_{ni}	$\{0, 1\}$, Caching decision for the i-th file to C_n
y_i	$\{0, 1\}$, Caching decision for the i-th file to the satellite

ground. In this case, the file will be obtained from a certain sever in Internet.

B. File Popularity Model

Note that content is delivered in forms of the flies in this paper. The file in caches are ranked from the most popular to the least according to its popularity. $\mathcal{F}$ indicates that collection of files with total files number F=$|\mathcal{F}|$. p_{ni} denotes the popularity of the i-th file at C_n, which follows the Zipf-like distribution. We can obtain

$$p_{ni} = \frac{R_n(i)^{-z_n}}{\sum_{n=1}^{N} R_n(i)^{-z_n}} = \frac{R_n(i)^{-z_n}}{\alpha_n}, \tag{1}$$

where α_n is a constant to normalize the request rate, $R_n(i)$ represents the popularity rank of the i-th file at C_n, and z_n is a parameter taking values in [0.6,1.2]. A larger value for z_n indicates a catalog that contains relatively small set of very popular files.

C. Satellite Channel Model

The signal envelope r in a satellite channel is modeled by shadowed Rice distribution based on [9]. The probability density function of Rice distribution is:

$$p(r) = \frac{r}{\sigma^2} \exp(-\frac{r^2 + r_s^2}{2\sigma^2}) I_0(\frac{r_s}{\sigma^2}), r \geq 0, \tag{2}$$

where r_s is the amplitude of the direct wave, $2\sigma^2$ is the total power of multipath components, and I_0 is the zero-order modified Bessel function. Since the total power of the multipath components changes with time, it is assumed that satellite bandwidth of uplink and downlink are time-varied functions denoted by $B_u(t)$ and $B_d(t)$, respectively, which are associated with Eq.(2).

III. PROBLEM FORMULATION AND SOLUTION

In this section, we formulate the joint caching optimization problem in the proposed two-layer caching model as a NLIP problem. Furthermore, we propose a caching strategy based on the genetic algorithm to solve the problem efficiently. The descriptions of symbols are summarized in Table I.

A. Problem Formulation

We assume that the total number of requests at C_n follows Poisson distribution with mean arrival rate λ_n and λ_{ni} denotes the request rate for the i-th file at C_n. We also assume that the request probability for the i-th file at C_n can be modeled by the file popularity model. So we can obtain

$$\lambda_{ni} = p_{ni}\lambda_n. \tag{3}$$

Requests not satisfied by ground stations are forwarded to the satellite and λ_{0i} denotes the average arrival rate of the i-th file in the satellite. Ground stations are sparsely distributed on a wide range of areas, so they are assumed to operate independently. According to the sum of Poisson processes Theorem [10], the average request arrival rate of the i-th file at the satellite is given by:

$$\lambda_{0i} = \sum_n (1 - x_{ni})\lambda_{ni}, \tag{4}$$

where binary variable $x_{ni} \in \{0, 1\}$ denotes caching decision for the i-th file to the C_n. x_{ni} takes 1 if the i-th file is cached at C_n, which also means the request for the i-th file will not be forwarded to the satellite, and takes 0 otherwise.

An aggregation window is set in the satellite to aggregate the requests during a given time, denoted by τ. Let $p_i(x_{ni})$ denote the probability of at least one request for the i-th file received by the satellite during τ. From Eq.(4), the number of requests for the i-th file at the satellite follows Poisson distribution with mean arrival rate λ_{0i}, we can obtain:

$$p_i = 1 - e^{-\lambda_{0i}\tau}. \tag{5}$$

A binary variable y_i indicates whether the i-th file is cached in the satellite. y_i takes 1 if the i-th file is cached in the satellite. Let s_i denote the size of the i-th file. Within τ, downlink bandwidth consumption is divided into two parts: $\sum_{i=1}^{I} p_i y_i s_i$ (caused by files cached in the satellite) and $\sum_{i=1}^{I} p_i(1-y_i)s_i$ (caused by the files relayed by satellite originated from the Internet). Then total entire downlink bandwidth consumption is $\sum_{i=1}^{I} p_i s_i$. Besides within τ, Internet needs to send files to the satellite and uplink bandwidth consumption is $p_i \sum_{i=1}^{I}(1 - y_i)s_i$. Since the goal is to minimize uplink traffic and downlink bandwidth consumption simultaneously, these two objectives are combined using a weight factor ω. Thus, we obtain a objective function:

$$minimize \;\; \omega \sum_i p_i s_i + (1 - \omega) \sum_i p_i(1 - y_i)s_i \tag{6}$$

subject to:

$$\sum_i p_i s_i \leq \int_\tau B_d(t)dt, \tag{7}$$

$$\sum_i p_i(1-y_i)s_i \leq \int_\tau B_u(t)dt, \tag{8}$$

$$\sum_i x_{ni}s_i \leq S_n,\ \forall n, \tag{9}$$

$$\sum_i y_i s_i \leq S_0, \tag{10}$$

$$x_{ni} \in \{0,1\},\ \forall n, \forall i, \tag{11}$$

$$y_i \in \{0,1\},\ \forall i, \tag{12}$$

where ω represents a weight factor to distinguish the importances of two satellite links. Smaller ω means less cost of downlink traffic in the system.

Constraints (7) and (8) guarantee that uplink traffic and downlink traffic should not exceed uplink and downlink bandwidth capacity, respectively. Constraints (9) and (10) emphasize that the total size of the cached files should not be greater than the maximum cache size of ground stations or the satellite. Finally, the set of constraints (11) and (12) express the integer nature of the decision variables.

This is a typical NLIP problem and its complexity increases with the increasing number of the files. Besides, since all the requests from ground stations are aggregated at the satellite during τ, the objective function in Eq.(6) has an exponentially long description in the number of ground stations N.

B. Solution

After the discussion of the objective function, we know the size of the solution space grows at an exponential rate with the total number of files I and ground stations N. It is an NP-Hard problem.

Hence, we propose a heuristic algorithm to solve this problem. Genetic algorithm is a stochastic optimization method inspired by the theory of evolution: through repeated natural selection over multiple generations, the last survival is the fittest [11]. In our optimization problem, the binary variables x_{ni}, y_i correspond exactly to the chromosome of individual in genetic algorithm.We let $x_j^k = \{x_{11}...x_{1I}, x_{21}...x_{NI}\}$ and $y^k = \{y_1, y_2...y_I\}$ represent the caching strategy in the first and second layer of individual j in generation k, respectively. V_j denotes the corresponding fitness value. Each function in genetic algorithm is explained and Algorithm 1 shows the procedure of genetic algorithm:

Initialization: Generate S^p initial chromosomes $\{x_j^1, y_j^1\}$ as first generation of individuals, which is generated by randomized;

Fitness Function: Calculate fitness value V_j of different individuals $\{x_j^k, y_j^k\}$, copy the individual which has optimum fitness value V^* as $\{x^*, y^*\}$ to next generation;

Selection: Make comparison of all fitness value and eliminate individuals which have worse fitness value with higher probability;

Crossover and Mutation: Apply genetic operations including crossover and mutation with probability ρ_c and ρ_m to get next generation of individuals $\{x_j^{k+1}, y_j^{k+1}\}$. All individuals must satisfy all the constraints from (7) to (10).

Algorithm 1 Genetic Algorithm

Input: S^g: generation size; S^c: chromosome size; S^p: population size; ρ_c: crossover rate; ρ_m: mutation rate;
Output: $\{x^*, y^*\}$: best individual; V^*: best fitness value;

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1: {x_j^1, y_j^1} =Initialization(S^c, S^p), ;
2: for k = 1; k < S^g; k++ do
3:     {x*, y*}, V_j, V* =Fitness Function(x_j^k, y_j^k);
4:     {x_j^k, y_j^k} =Selection(x_j^k, y_j^k, V_j);
5:     {x_j^k, y_j^k} =Crossover(x_j^k, y_j^k, ρ_c);
6:     {x_j^k, y_j^k} =Mutation(x_j^k, y_j^k, ρ_m);
7: end for
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Note that our fitness function is the objective function in Eq.(6) and we set $\omega = 0.3$. In every generation, the optimum individual is chosen and passed to the next generation. The position of crossover and mutation is chosen at random.

Now we analyse the complexity and convergence of genetic algorithm. The genetic algorithm we employ maintains the best individual in each generation. According to [12], it could finally converge to the global optimal solution. But it is time-consuming to obtain optimal solution for a large-scale problem. In this case, we let the algorithm terminate in a finite number of iterations so that we can obtain a near-optimal solution within a time limit. Besides, we associate the number of ground stations with the number of files, i.e. $N = \mu \cdot I$. Then the time complexity for each iteration is $O(I^2 \cdot S^p)$.

IV. NUMERICAL RESULTS

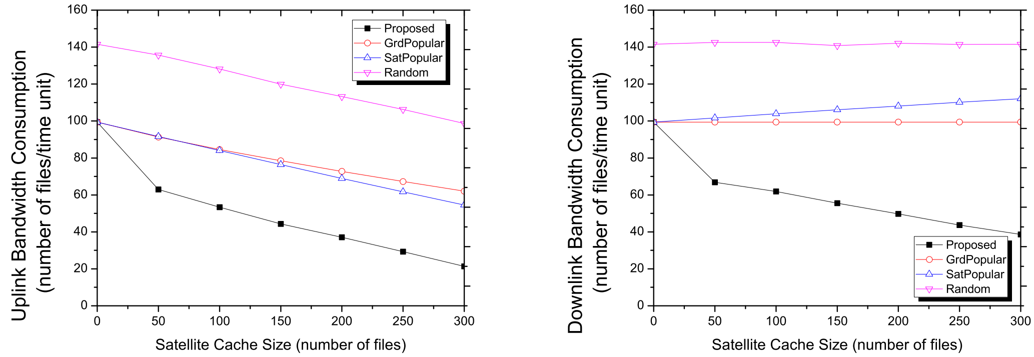
In traditional satellite-terrestrial networks, caching the most popular files in the ground stations will save massive satellite uplink and downlink bandwidth. But this local optimal strategy may be not suitable in our two-layer caching model. Thus, we compare our caching strategy with other three strategies in satellite bandwidth consumption and find out the behavior of optimal strategy.

GrdPopular Strategy: Each ground station chooses the most popular files to cache, and the satellite caches the most popular files in the rest of these files.

SatPopular Strategy: The satellite caches the most popular files at first, then ground stations choose the most popular files in the rest of these files to cache.

Random Strategy: The satellite and ground stations randomly choose files to cache.

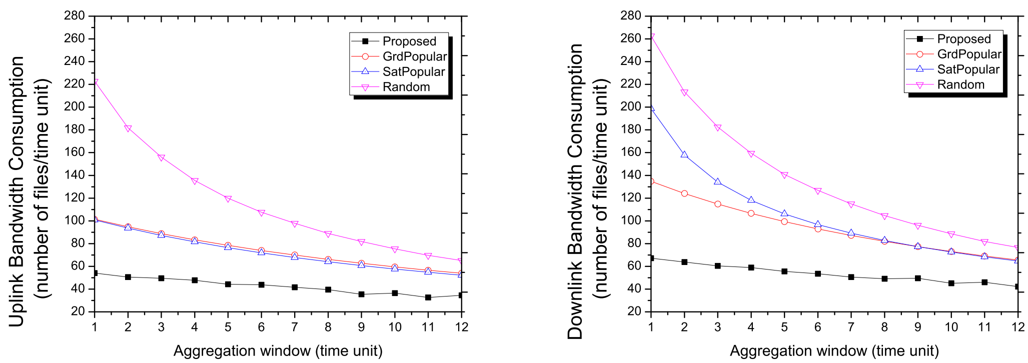
For simplicity, we consider unit time, and all files have the same size normalized to 1. Hence, the following parameters are used: $I = 1000$ and $N = 10$. As we focus on the influence of satellite cache, we set a constant ground cache size, $S_n = 300,\ n \in \{1, 2...N\}$. The arrival rate $\lambda_n = 50,\ n \in \{1, 2...N\}$. File popularity at each ground station is independent. The numerical results are given by genetic algorithm with 30 candidate solutions in each generation, and



(a) Uplink

(b) Downlink

Fig. 2. The impact of cache size on uplink (a) and downlink (b) satellite bandwidth consumption ($z = 0.8, T = 5$).



(a) Uplink

(b) Downlink

Fig. 3. The impact of aggregation window size on uplink (a) and downlink (b) satellite bandwidth consumption ($z = 0.8$).

the number of iterations is set to 3000. We set the probability of crossover and mutation operation is 1 and 0.1, respectively.

A. *Impact of Cache Size on Satellite Bandwidth Consumption*

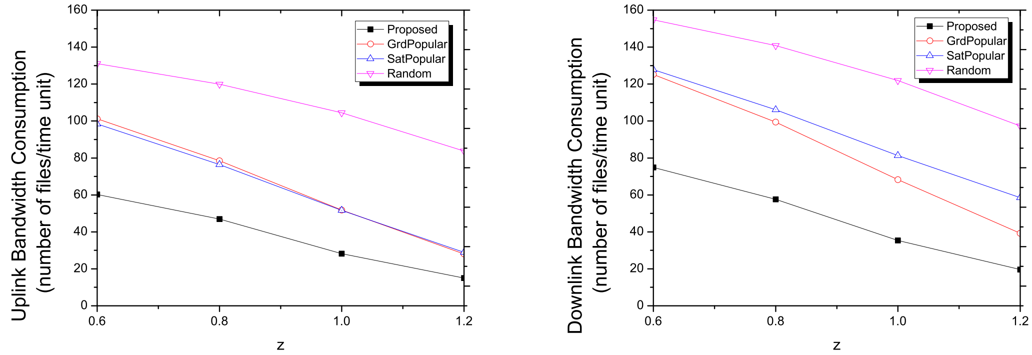
From Fig. 2, we can see that satellite bandwidth consumption of all caching strategies decreases almost linearly in both uplink and downlink directions with the increasing cache size in the satellite. When the cache size in the satellite grows to 17% of constant cache size in the ground station, our proposed strategy can save 37% and 33% satellite bandwidth in both uplink and downlink directions, respectively. Compared with GrdPopular Strategy, the numbers decline to 31% and 33% but still are considerable. Moreover, when satellite cache size is the same as that of ground caches, our proposed strategy can save 60% bandwidth compared with SatPopular Strategy.

The main difference between proposed strategy and popularity aware strategies such as GrdPopular is that, GrdPopular always caches the most popular files in each ground station. In our proposed two-layer caching architecture, if we cache a file in the satellite, the same requests for the file from ground stations only need to be responded once due to the broadcast nature. Therefore, global popular files should be cached in the satellite, which makes limited ground caches have more space to cache other less popular files and decreases the total satellite bandwidth consumption. Besides, the additional satellite cache also has significantly influence on caching strategy in layer 1.

B. *Impact of Aggregation Window on Satellite Bandwidth Consumption*

The results plotted in Fig.3 show the downtrend of the satellite bandwidth consumption as the aggregation window increases. The performance of proposed strategy is most stable among all caching strategies. At the beginning of Fig.3(a) and Fig.3(b), our proposed strategy saves 46.7 and 125.5 units bandwidth compared with GrdPopular Strategy in both uplink and downlink directions, respectively. But when aggregation window τ reaches 12, our proposed strategy can only save 40 units of satellite bandwidth in total compared with SatPopular Strategy, and the satellite bandwidth consumption of SatPopular Strategy only has 116.8 units in total.

This is due to the fact that saved satellite bandwidth in our proposed strategy already reaches upper limits. Setting a large aggregation window does not help much to improve the performance of our proposed strategy. But in practical



(a) Uplink

(b) Downlink

Fig. 4. The impact of different popularity of files on uplink (a) and downlink (b) satellite bandwidth consumption ($T = 5$).

system, without the limitation of total number and arrival rate, it is still necessary to set a reasonable aggregation window for saving more satellite bandwidth. Last, satellite bandwidth consumption in Random Strategy decreases fastest because that the request probability of these unpopular files increases with the increasing of aggregation window.

C. Impact of Diversity of Popularity on Satellite Bandwidth Consumption

In Fig.4, we plot the relationship between satellite bandwidth consumption and the popularity distribution of different files. z_n is the exponential parameter of Zipf distribution which influences the popularity of content files in the n-th ground station. When z_n is small (e.g., $z_n = 0.6$), the popularity of files between rank 1 and rank 10 could be similar. In our numerical results, we set z_n as z for all ground stations.

Fig.4(a) and Fig.4(b) show the downtrend of the satellite bandwidth consumption. We can observe that the interval between proposed strategy and GrdPopular Strategy becomes smaller with the increasing of parameter z. For instance, saved uplink bandwidth of proposed strategy compared with GrdPopular Strategy declines from 41 to 12.9 units when $z = 0.6$ and $z = 1.2$ in Fig.4(a), and downlink from 50.3 to 19.6 units in Fig.4(b). This is because the increasing diversity of popularity with the increasing of z makes more requests centralize on a few files and the rest files barely get requested, thus our proposed strategy and GrdPopular Strategy both tend to cache these popular files in ground stations for saving more bandwidth.

V. CONCLUSION

In this paper, we propose a two-layer caching model for content delivery services in the satellite-terrestrial network. To minimize satellite bandwidth consumption, joint caching optimization between the satellite and ground stations is formulated as a NLIP problem, where a aggregation window is involved to exploit the broadcast advantage of the satellite. Furthermore, the genetic algorithm is proposed to solve the problem efficiently. Numerical results show that the proposed caching strategy outperforms content popularity aware and random caching strategies significantly.

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