Content-Aware Routing based on Cached Content Prediction in Satellite Networks

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Abstract—As a promising complement to terrestrial cellular networks, such as 5G/6G, satellite networks have recently drawn increasing attention. However, facing the challenges of the rapidly increasing users' demand for multimedia content, how to achieve efficient data delivery in a dynamic environment becomes a critical but knotty problem. To provide an efficient solution from the routing perspective, in this paper, we consider the Information-Centric Networking (ICN) architecture and propose a content-aware routing scheme. The basic idea of the proposed routing scheme is to leverage the cached content on cache-enabled satellites and find the optimal route solution with maximum net-gains, i.e., how much delay is reduced. Considering the limitation of periodical signaling collection in satellite networks, we also design a cached content prediction model, which can infer the probability that a certain content could be cached according to the content's historical popularity information, to provide necessary information to measure net-gains. Extensive simulation results show that the proposed content-aware routing scheme outperforms the traditional routing scheme with a 20% reduction in terms of content retrieval delay and traffic consumption.

Index Terms—Satellite networks, information-centric networking, content-aware routing, cached content prediction

I. Introduction

As a promising complement to the terrestrial cellular system, satellite networks have experienced rapid development to stride toward large-scale Satellite-Terrestrial Integrated Networks (STINs) in 5G/6G era [1]. Due to the characteristic of high altitude and broadcast, satellite networks can provide seamless coverage without the requirement of infrastructure [2], which is attractive to terrestrial users located in rural areas, oceans and etc. In the future, it can be foreseen that terrestrial users can obtain ubiquitous services such as Internet access and content retrieval through STINs.

Unfortunately, users' demand for multimedia content has increased tremendously in recent years [3], [4]. The increasing content traffic generated by numerous applications challenges the capability of data delivery in satellite networks. Even though the routing problem, as the key function that provides the route guidance for data delivery, has been studied for years and plenty of routing schemes have been proposed and designed for satellite networks [5], [6], the current capability of Inter-Satellite Links (ISLs) still hinders the improvement of data delivery in satellite networks, which makes the demand of content traffic can hardly be satisfied.

To solve such a knotty problem, the existing work further adopts Information-Centric Networking (ICN) architecture [7], which is characterized by two major features, i.e., routing-by-name and in-network caching, to offload the redundant traffic from users' requests for popular content and thus significantly improve the efficiency of data delivery in satellite networks. For example, Galluccio *et al.* [8] and Tomaso *et al.* [9] first introduced ICN into satellite networks and designed the specific protocol architecture to achieve content-aware function, and the extensive simulation results also show effectiveness the ICN in satellite networks. Based on that, Li *et al.* [10] further proposed a novel architecture that combines Software-Defined Networking (SDN) and ICN to provide flexible management and efficient content retrieval for the STIN. The Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO) satellites are considered as the controller to globally control the caching strategy and content delivery process of Low Earth Orbit (LEO) satellites. After that, Yang *et al.* [11] focused on the specific content retrieval process in ICN-based satellite networks, and devised a reliable and efficient content retrieval scheme through coding-enabled multicast model to provide an interference-tolerant, low-latency, and efficient content delivery service.

Although the effectiveness of ICN architecture has been validated in satellite networks, most of the existing studies mainly focus on the optimization of caching and transmission strategy, and an efficient routing design with content-aware function in satellite networks is still missing. Meanwhile, since the constraint of the dynamic environment and communication overhead, the global caching information can hardly be collected through ISLs in real time, thus, the current content-aware routing design in terrestrial ICN-enabled networks cannot be applied to satellite networks directly [12], [13]. In this case, how to design an efficient content-aware routing scheme becomes a critical but unsolved problem.

To fully utilize the resource of in-network caching provided by ICN architecture and provide efficient data delivery service for content traffic, in this paper, we apply the content-aware feature of ICN to satellite networks and propose a content-aware routing scheme that utilizes the prediction information of cached content in the network and find the optimal solution with maximum *net-gains*. At first, considering the overhead of real-time information collection in dynamic satellite networks,

each satellite can only be informed of the cache status of other satellites periodically, thus, we design a prediction model that allows satellites to predict the probability of a certain content being cached by other satellites from periodically updated signaling. Based on the predicted probability of cached content, we further propose a content-aware routing algorithm that can undertake tolerable risks to retrieve the content from a nearby satellite with lower delay. To evaluate the performance of the proposed prediction model and the content-aware routing algorithm, we also conduct extensive simulations, and results verify the accuracy of the proposed prediction model and show the superiority of the proposed routing scheme compared with existing routing schemes in satellite networks.

The contributions of the paper are summarized as follows:

- We design a prediction model to estimate the cached content on each satellite in the network through historical popularity information. The proposed prediction model can provide precise and necessary information for content-aware routing decision.
- Based on the predicted probability of cached content, we further propose a content-aware routing scheme in satellite networks. The proposed routing scheme utilizes the prediction information of cached content in the network and find the optimal node for retrieving content with the maximum *net-gains*.
- We conduct extensive simulations compared with existing schemes to evaluate the performance of the proposed content-aware routing based on cached content prediction. The results show significant reduction of the proposed schemes in terms of delivery delay and traffic consumption.

The rest of the paper is organized as follows: the system model is introduced in Section II and the cached content prediction model and theoretical analysis are discussed in Section III. After that, the content-aware routing design based on the cached content prediction is proposed in Section IV. Finally, the performance evaluation and analysis conducted in Section V, and conclusions are drawn in Section VI.

II. SYSTEM MODEL

A. Satellite Network Model

The satellite network architecture consists of LEO satellites and MEO/GEO satellites. LEO satellites are denoted as $\mathcal{L} = \{L_1, L_2 \cdots L_I\}$ where $I = |\mathcal{L}|$ is the number of LEO satellites. As shown Fig.1, LEO satellites are responsible for the access of terrestrial users and the forwarding process of request and content. Meanwhile, part of LEO satellites are satellites with caching capabilities, and they will update their caches according to real-time users' requests under the guidance of certain caching strategies such as Least Frequently Used (LFU), Least Recently Used (LRU), etc. Besides MEO/GEO satellites act as helpers [14] in our scheme due to the advantage of wide coverage, which collect global popularity information through periodical signaling, i.e., the

popularity tables of all cache-enabled satellites, and broadcast it to all LEO satellites in the network.

In addition, access satellite is the LEO satellite closest to the terrestrial users, and publisher is a satellite which has cached the requested content or can communicate with the ground gateway. In other words, each access satellite in the network can definitely retrieve requested content from publisher.
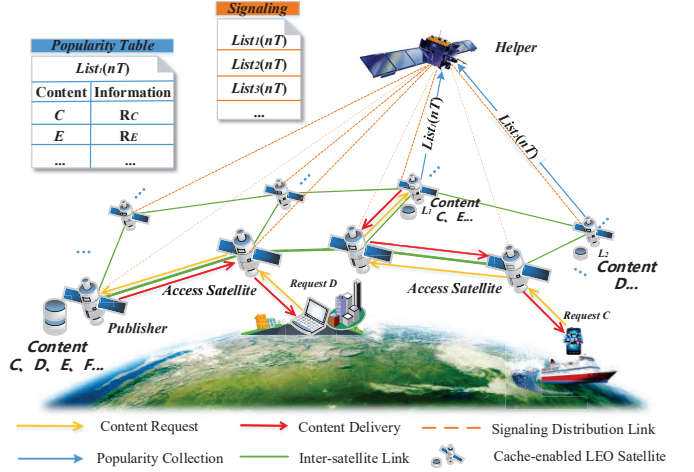

Fig. 1. Network architecture of our scheme.

B. In-network Caching and Request Model

The total content library is depicted as $\mathcal{C} = \{C^1, C^2 \cdots C^J\}$ where $J = |\mathcal{C}|$ is the number of all content. In addition, the request for content C^j is denoted as R^j and the process of request R^j arrival at the satellite L_i obeys a Poisson process with arrival rate $\lambda_i^j(t)$. Meanwhile, in order to have a better cache performance and perceive the popularity information of cached content, each cache-enabled satellite maintains one popularity table, denoted as $List_i(t)$. Each cache-enabled satellite updates its local popularity table in real time. Every time it receives a request R^j for content C^j, regardless of whether the content exists in this satellite's cache, the request information will be recorded to the popularity table.

Without loss of generality, this paper assumes that each content has same size M bytes, and each cache-enabled satellite has the same cache size s, i.e., it has $s \cdot M$ bytes of storage space. Each satellite updates cached content according to the content popularity ranking in the popularity table. In specific, content C^j can be cached if its popularity $p_i^j(t)$ satisfies

$$p_i^j(t) > p_i(t), \tag{1}$$

where $p_i(t)$ is the cache threshold at time t in the satellite L_i. We determine the cache threshold of each node according to its cache size, that is, the top s popular content in the popularity table $List_i(t)$ will be cached and $p_i(t)$ is the s-th content's popularity at time t.

C. Popularity Information Update Model

Consider that helpers collect all cache-enabled satellites' popularity tables every T time interval, which is denoted as

$$Lists(nT) \triangleq \{List_1(nT), List_2(nT)\cdots\}, \qquad (2)$$

where number n represents the number of times helpers collect the total popularity tables of all cache-enabled satellites. Then helpers broadcast and distribute $Lists(nT)$ to each LEO satellite. In specific, popularity table $List_i(nT)$ records the popularity information of all requests reaching at satellite L_i up to time nT [15]. The popularity information for content C^j till time nT is denoted as $\mathcal{R}_{(nT)}^{(j)} \triangleq \{0 < \tau_1^{(j)}\cdots\tau_i^{(j)}\cdots\tau_{k_{(nT)}^{(j)}}^{(j)} \le nT\}$, where $\tau_i^{(j)}$ is the arrival time of i-th request out of $k_{(nT)}^{(j)}$ for content C^j up to nT.

In a practical satellite network, one thing has to be noticed is the overhead of the collection and update of popularity information. If the helpers collect and distribute all cache-enabled satellites' popularity tables in real time. In this case, the nodes in the network can easily know what specific content is currently cached on a certain satellite according to its real-time popularity table. However, the way of collecting popularity tables in real-time consumes too many resources. Considering the overhead of signaling interaction and propagation delay of ISLs, in practice, the helpers prefer to execute periodical information (i.e., popularity tables of each cache-enabled satellite) collection and distribution process, and the period of update process denotes as T. Besides, the signaling periodically distributed by helpers contains all LEO satellites' popularity tables and their cache status.

III. Cached Content Prediction Model

A. The Probability of Cached Content on Satellite

Since helpers collect and update the popularity tables in discrete time interval rather than in real time, satellites cannot perceive the cache of other satellites at any time and precisely know at which satellite the requested content is cached. However, one satellite can predict the probability of the content cached at other satellites according to the historical popularity information of the content in the total popularity table $Lists(nT)$ distributed last time. Thus, we design a cached content prediction model, it can provide the probability P_i^j that content C^j has been cached on the satellite L_i at time t,

$$P_i^j(t) = \Pr\left(p_i^j(t) > p_i(t)\right). \qquad (3)$$

Meanwhile, the probability that the content has not been cached at the satellite L_i is calculated by $\overline{P}_i^j(t) = 1 - P_i^j(t)$.

Define the popularity of content C^j at satellite L_i as

$$p_i^j(t) = \frac{N_i^j(t)}{N_i(t)}, \qquad (4)$$

where $N_i^j(t)$ and $N_i(t)$ denote the request times of content C^j and total request times at the satellite L_i till time t. Note

that each cache-enabled satellite maintains a popularity table to record every content's popularity information $\mathcal{R}_{(t)}^{(j)}$.

Consider at time t ($t = nT + \tau, 0 \le \tau < T$), the popularity of content C^j and the cache threshold at satellite L_i are denoted as $p_i^j(nT + \tau)$ and $p_i(nT + \tau)$, where nT is the time when helpers distributed signaling last time. According to (4), the popularity $p_i^j(t)$ can be calculated by

$$
\begin{aligned}
p_i^j(t) = p_i^j(nT + \tau) &= \frac{N_i^j(nT + \tau)}{N_i(nT + \tau)} \\
&= \frac{N_i^j(nT) + N_i^j(nT, nT + \tau)}{N_i(nT) + N_i(nT, nT + \tau)} \\
&= \frac{1}{1 + N_i(nT, nT + \tau)/N_i(nT)} p_i^j(nT) \\
&+ \frac{1}{N_i(nT + \tau)} N_i^j(nT, nT + \tau).
\end{aligned}
\qquad (5)
$$

where $N_i^j(nT, nT + \tau)$ represents the requested times of content C^j during $(nT, nT + \tau)$. Therefore, the probability $P_i^j(t)$ in (4) can be further denoted as

$$
\begin{aligned}
P_i^j(t) &= \Pr\left(p_i^j(nT + \tau) > p_i(nT + \tau)\right) \\
&= \Pr\left(N_i^j(nT, nT + \tau) > K\right),
\end{aligned}
\qquad (6)
$$

where the number K represents how many times the request R^j should arrive during (nT, t) if the content C^j could be cached at satellite L_i.

$$
\begin{aligned}
K &= (N_i(nT) + N_i(nT, nT + \tau))\, p_i(nT + \tau) \\
&- \frac{N_i(t) + N_i(nT, nT + \tau)}{1 + N_i(nT, nT + \tau)/N_i(nT)} p_i^j(nT).
\end{aligned}
\qquad (7)
$$

Let $p_i(nT + \tau) = (1 + w)p_i(nT)$, where w is the correction factor and it can be obtained by training. We assume that the process of request R^j arrival at the satellite L_i obeys a Poisson process with arrival rate $\lambda_i^j(t)$. Besides, the arrival rate of all requests, denoted as $\overline{\lambda}_i(t)$, is equalled to the average arrival rate before nT, i.e., $\overline{\lambda}_i(t) = \frac{N_i(nT)}{nT}$. Hence, $N_i(nT, nT + \tau) = \overline{\lambda}_i(t)\tau$, and the number K can be further calculated by

$$
\begin{aligned}
K &= \left(N_i(nT) + \overline{\lambda}_i(t)\tau\right)(1 + w)p_i(nT) \\
&- \frac{N_i(nT) + \overline{\lambda}_i(t)\tau}{1 + \overline{\lambda}_i(t)\tau/N_i(nT)} p_i^j(nT),
\end{aligned}
\qquad (8)
$$

which could definitely be known or inferred from the popularity table $List_i(nT)$.

Since the arrive process of request R^j obeys a Poisson process with arrival rate $\lambda_i^j(t)$, so $N_i^j(nT, nT + \tau) = N_i^j(\tau)$. Therefore, the probability in (6) can be rewritten as

$$
\begin{aligned}
P_i^j(t) &= \Pr\left(N_i^j(\tau) > K\right) \\
&= 1 - \sum_{n=0}^{\lceil k \rceil}\left(e^{-\lambda_i^j(t)\tau}\frac{\left(\lambda_i^j(t)\tau\right)^n}{n!}\right),
\end{aligned}
\qquad (9)
$$

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where the $\lambda_i^j(t)$ can be calculated by the historical information $\mathcal{R}_{(nT)}^{(j)}$ from the popularity table $List_i(nT)$. To fully reflect the accuracy of the arrival rate $\lambda_i^j(t)$, define

$$\lambda_i^j(t) = \frac{\tau_{k_{(nT)}^{(j)}}^{(j)} - \tau_{k_{(nT)}^{(j)}-1}^{(j)}}{2}, \tag{10}$$

where $k_{(nT)}^{(j)}$ represent the total requests times of content C^j before time nT at satellite L_i.

B. The Influence of Correction Factor w

In the last subsection, we propose our cached content prediction model. An important assumption is that we let

$$p_i(nT + \tau) = (1 + w)p_i(nT), \tag{11}$$

where the w is a very tiny value. The relationship between $p_i(nT + \tau)$ and $p_i(nT)$ can be considered from two aspects: first, the degree of change in the number of requests arriving at satellite L_i; second, the time span τ. We find that w is not a stationary value within one signaling distribution period T, but dynamically fluctuates in the range (w_{min}, w_{max}). The influence of changing the value of correction factor w is reflected on the change of K. If we take a more conservative strategy, we can set $w = w_{max}$. The conservative strategy means we set a higher cache threshold for caching content. Then the probability of the content C^j being cached at the satellite will be conservatively predicted due to the value of K increases with the setting $w = w_{max}$. In order to reduce the probability of error of cached content prediction, we adopt a more conservative strategy, $w = w_{max}$.

IV. CONTENT-AWARE ROUTING SCHEME

Based on the prediction model in the last section, each access satellite can obtain the probability that content C^j has been cached on the satellite L_i at time t, i.e., $P_i^j(t)$. In this section, we further propose a content-aware routing algorithm.

A. Net-gains of The Optimal Node

Due to the uncertainty of cached content on each satellite, we define satellites which are possible to have cached the content C^j as the possible optimal nodes, denoted as $\mathcal{L}^j$. After one access satellite receives a request, it will find the possible optimal nodes $\mathcal{L}^j$, and calculate the *net-gains* of these nodes according to the following function:

$$M_i = P_i^j(t)Gain_i - \overline{P}_i^j(t)Risk_i, \forall i \in \mathcal{L}^j, \tag{12}$$

where $Gain_i$ represents the gains on time that the access satellite S forwards the request to the possible optimal node L_i rather than forward the request to the publisher D. Thus,

$$Gain_i = \sum_{(u,v) \in P(S,D)} T(u,v) - \sum_{(u,v) \in P(S,L_i)} T(u,v), \tag{13}$$

where $P(S, D)$ denotes the path between node S and node D. Meanwhile, time $T(u, v)$ represents the summary of the propagation delay and the transmission delay at the satellite u and v, i.e., $T(u,v) = T_{(u,v)}^{Prop} + T_u^{Trans}$.

Algorithm 1: Content-aware Routing Based On Cached Content Prediction

Input: request R^j, content publisher D, current time $t = nT + \tau$, total popularity tables $Lists(nT)$;
Output: the path to the optimal node for retrieving content C^j: $P(S, L_o)$;

1 **Step1 Find the optimal possible nodes $\mathcal{L}^j$:**
2 Initialize a set $\mathcal{L}^j = \emptyset$
3 **for** each $List_i(nT) \in Lists(nT)$ **do**
4 　　Calculate the probability $P_i^j(t)$ according to (9);
5 　　**if** $P_i^j(t) > 0$ **then**
6 　　　$\mathcal{L}^j \leftarrow \mathcal{L}^j + L_i$
7 　　**end**
8 **end**
9 **Step2 Choose the optimal node L_o:**
10 Initialize $L_o = D$, $M_o = 0$;
11 **for** each $L_i \in \mathcal{L}^j$ **do**
12 　　Find paths $P(S, L_i)$ and $P(S, L_i, D)$ according to $Dijkstra$;
13 　　Measure the *net-gains* M_i for going to L_i, $\forall L_i \in \mathcal{L}^j$, according to (12);
14 　　**if** $M_i > 0$ **then**
15 　　　$L_o = L_i$, $M_o = M_i$;
16 　　**end**
17 **end**
18 **Step3 Find path to the optimal node:**
19 Find path $P(S, L_o)$ according to $Dijkstra$;
20 **return** $P(S, L_o)$

The previous item in (13) is the delay between the access satellite S and the content publisher D, and the latter item represent the delay between the access satellite S and the possible optimal node L_i. $Gain_i$, the discrepancy between the previous item and the latter, denotes the gains on time that the access satellite S successfully retrieve the content C^j from the possible optimal node L_i.

Similarly, $Risk_i$ represents the time spent in vain in such a situation where the access satellite S incorrectly predicts that the content C^j has been cached by satellite L_i and forwards the request to L_i. Thus, $Risk_i$ can be calculated by

$$Risk_i = \sum_{(u,v) \in P(S,L_i,D)} T(u,v) - \sum_{(u,v) \in P(S,D)} T(u,v), \tag{14}$$

where $P(S, L_i, D)$ denotes the two paths that consist of path $P(S, L_i)$ and path $P(L_i, D)$. Hence, the discrepancy between the previous item and the latter in (14) represents the risks on time that the access satellite S unsuccessfully fetch the content C^j from the possible optimal node L_i.

Summarily, M_i in (12) is the *net-gains* of going to the possible optimal node L_i for retrieving content C^j. Therefore, the optimal node for retrieving content C^j is denoted as

$$L_o = \arg\max(M_i), \forall L_i \in \mathcal{L}^j. \tag{15}$$

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B. Content-aware Routing Algorithm

The steps to find the possible optimal nodes $\mathcal{L}^j$ for content C^j and find the path to the optimal node L_o are described as Algorithm 1. One access satellite will measure the *net-gains* of going to these possible optimal nodes $\mathcal{L}^j$ for retrieving content C^j, and select the node with maximum *net-gains* as the optimal node L_o. After that, the access satellite will forward the request R^j to the optimal node. By doing this, we achieve a content-aware routing scheme based on cached content prediction model in satellite networks.

V. PERFORMANCE EVALUATION

We adopt an open-source Large-scale Satellite Network Simulator (LSNS) [16] as our simulation environment. We take a real-world dataset based on MovieLens [17] which has 100,000 requests for 1682 movies to simulate the content requests sent by terrestrial users to access satellites. All experiments were performed on a PC with four 3.6GHz CPUs, 16GB RAM, and Windows 10 OS.

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Height of Orbits	1050km
Number of LEO	80
Number of Planes	8
Inclination	53 degrees
Bandwidth of ISLs	10Mbps
Cache Strategy	LFU
LFU Update Period	5s
Content Size	0.2MB

For performance comparison, we adopt the following three baseline schemes:

- *SPFR* : Shortest path first routing scheme but satellites without content-aware and cache-enabled capabilities.
- *CARS* : Content-aware routing based on Algorithm 1 but without cached content prediction in **STEP1**, i.e., $P_i^j(t) = 1$ if satellite L_i cached content C^j at time nT.
- *CARPS* : Content-aware routing based on cached content prediction, i.e., Algorithm 1.

TABLE II
PREDICTION ACCURACY.

Period T Scheme	5s	200s	400s	600s	800s
CARS	100%	79.2%	74.8%	67.5%	51.4%
CARPS	100%	95.7%	92.3%	89.8%	81.8%
IMPROVEMENT	0%	16.5%	17.5%	22.3%	30.4%

A. Prediction Accuracy Analysis

TABLE II shows the result that the effect of the signaling distribution period T on the prediction accuracy. Define $\beta = \frac{N_{correct}}{N_{false}+N_{correct}}$ as the prediction accuracy, where N_{false} represents how many times that the requested content is not found at the optimal node. Similarly, $N_{correct}$ represents the
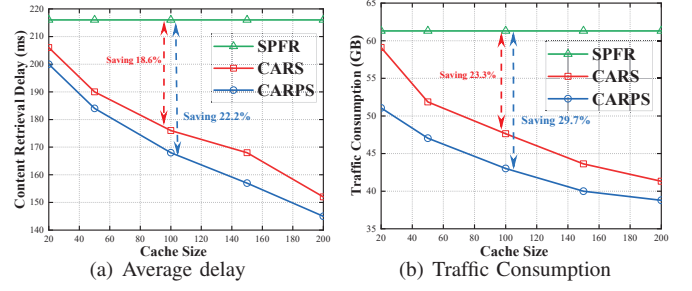

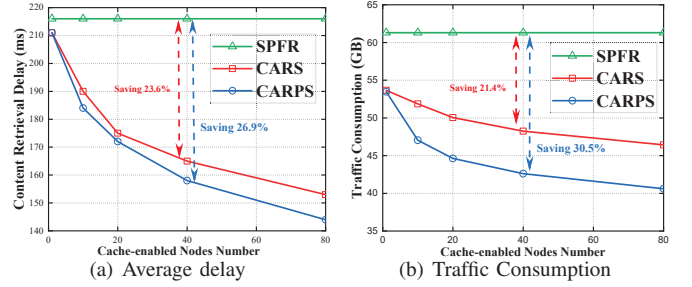Fig. 2. Performance Comparison Versus Different Cache Size.

Fig. 3. Performance Comparison Versus Different Cache-enabled Nodes Number.

times that the requested content is successfully retrieved at the optimal node. It can be observed that the prediction accuracy of CARS decreases with the increase of period T. When the period T for distributing popularity tables is closer to the period for cache updating, the prediction is more accurate. However, with the increase of T, the proportion of successfully retrieving content at the optimal node decreased considerably. The reason for this phenomenon is that the satellite cache is updated at very short intervals, i.e., the popular content in the popularity table of the previous signaling distribution may be replaced soon. While other satellite nodes cannot obtain the real-time cache of it and still think the content has been cached on this satellite, which will lead to prediction errors. If we adopt CARPS, it will bring a very significant improvement in accuracy performance, and reduce the delay of content retrieval and traffic consumption.

B. Performance Comparison Versus Different Settings

Next, we evaluate the performance of different cache settings, including the cache size and the number of cache-enable satellites. Fig.2 shows the performance of different cache size. It can be observed that the content retrieval delay and traffic consumption decrease with the increase of cache size because more popular content can be cached. Therefore, a satellite is more likely to successfully retrieve content from a cache-enabled satellite after receiving a request from a terrestrial user. Fig.3 shows the performance with different scale cache-enabled nodes. This scenario is similar to that of a terrestrial content delivery network, which allows access satellites to retrieve content from closer satellites rather than remote content publisher. In addition, compared with SPFR

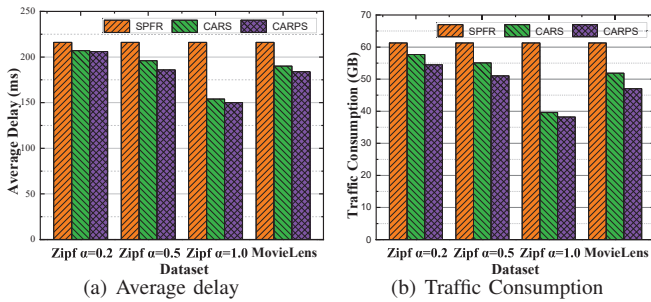(a) Average delay (b) Traffic Consumption

Fig. 4. Performance Comparison Versus Different Datasets.

and CARS, CARPS reduces content retrieval delay and traffic consumption by nearly 30% and nearly 10%.

C. Performance Comparison Versus Different Datasets

To verify the generality of our proposed scheme, we also adopt different synthetic datasets, which obey the Zipf [18] distribution with different exponents parameters. Fig.4 shows the performance under different datasets. We can see that CARPS has less content retrieval delay and traffic consumption compared to SPFR regardless of whatever dataset is used. Meanwhile, it can be observed that CARPS has different gain effects on datasets with different popularity distributions. With the increasing of Zipf distribution parameter, the performance improvement for using CARPS is more obvious. This is because terrestrial users' requests are converging on several popular contents with the increasing of distribution parameter α, thus cache-enabled satellites prefer to cache them for lower content retrieval delay and traffic consumption.

VI. CONCLUSION

In this paper, we proposed a content-aware routing scheme to provide efficient content delivery service in satellite networks. The basic idea is to leverage the cached content on cache-enabled satellites and find the optimal route solution with maximum *net-gains*, i.e., how much delay is reduced. In addition, considering the overhead of real-time information collection in dynamic satellite networks, each satellite can only be informed of the cache status of other satellites periodically, thus, we also designed a cached content prediction model based on historical popularity information. That is, a satellite node can predict the probability of a certain content being cached in other satellite nodes according to the historical popularity information which was periodically collected and distributed by helpers. Extensive simulations showed that the content-aware routing scheme based on cached content prediction algorithm outperforms the traditional shortest path first scheme in terms of content retrieval delay and traffic consumption in satellite networks.

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