# A Novel Adaptive Data Prefetching Scheme in Satellite-ground Integrated Networks with Edge Caching

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***Abstract*—The satellite-ground integrated network has been proposed to be one of the key technologies in the next-generation wireless communication network. However, in the network with low orbit satellites (LEO) as relay nodes to serve the backhaul, both the wireless access links and the backhaul links are changing rapidly. In this paper, we propose to deploy the software-defined network and edge caching to extend the concept of content prefetch from users to networks, which compensates for the poor transmission conditions in the satellite-ground mobile network. Specifically, an optimization problem is proposed for the prefetching scheme based on the current and predicted network state (e.g., the cache state of the user and the base station), and movement patterns of users and satellites. The problem is a mixed integer nonlinear problem, which then is transformed into convex to be solved effectively. The simulation results show that the proposed prefetching scheme can improve the users' experience.**

***Index Terms*—Satellite networks, satellite-ground integrated networks, prefetching, resource allocation**

## I. INTRODUCTION

Online video traffic is booming and occupies more than 70% of all total internet traffic [1]. For the video business, its ultimate purpose is to provide users with a smooth and high-quality video playback experience. However, the wireless channel gain of high-speed mobile users is likely to change a lot over time and it is impossible to establish wired backhaul links in some areas. These factors pose great challenges in providing good business. Fortunately, in the context of the convergence of satellite-ground networks, low-orbit satellites can be used as a supplement to the terrestrial wired backhaul links [2]. Due to the high-speed mobility of the satellite, the gain of the backhaul links changes more quickly. The rapid channel change in wireless links and backhaul links inevitably decreases the smoothness of videos. To compensate for the potential congestion of wireless and backhaul links and improve spectrum utilization efficiency, prefetch technology has been introduced in satellite-ground mobile networks [3].

Based on the location of the prefetched data, prefetching in mobile networks can be classified into two main categories: user equipment (UE) prefetching and access node (AN) prefetching. In [4], by predicting the data required by the user, the data is prefetched to the user's cache in advance, to realize the prefetching on the user side. Based on the Software-defined cellular network, reference [5] realizes prefetching the user's required data packets to the target. Quality of Experience (QoE)-based service management remains key for the successful provisioning of multimedia services in next-generation networks. In [6], the authors propose a QoE awareness co-optimization strategy combining SDN and cache resources to realize the sensing bandwidth supply in SDN and active cache according to user status. The combined prefetching strategy on different types of nodes can also improve performance. Reference [7] implements adaptive prefetching of data at users and access nodes so that data can be selected from appropriate cache nodes.

It can be seen that prefetching technology has been widely used in the mobile communication network as an important technology. However, there is a lack of research on the prefetching strategy for dynamic changes of both wireless and backhaul links in the satellite-ground convergence network. Fortunately, there are studies [8] that combine SDN with LEO satellite networks. Through the position prediction component in SDN, the position of low orbit satellite and user position can be predicted.

Therefore, aiming at the dynamic changes of wireless and backhaul links caused by satellites and users' movements, we develop a prefetching strategy in which the network can dynamically select the location and amount of prefetched data. In the strategy, we consider the buffer status of users and base stations as well as the status of channel links to allocate resources to radio access channels better. In addition, we also consider the mobility of users and satellites. By knowing the positions of users and satellites in the next time slot, we can predict the resources of the backhaul links and wireless access links. The predicted information can help the network determine whether to prefetch the content, which greatly improves the efficiency of links, reduces the probability of flow freezing and improves the users' QoE. We also propose a new framework and scheme supporting adaptive prefetch in this paper.

The rest of the paper is organized as follows. Section II introduces the system model and describes the general architecture of adaptive prefetching. Section III formulates the presented problem and presents the proposed algorithms. Simulation results are presented in Section IV. Finally, we conclude this paper in

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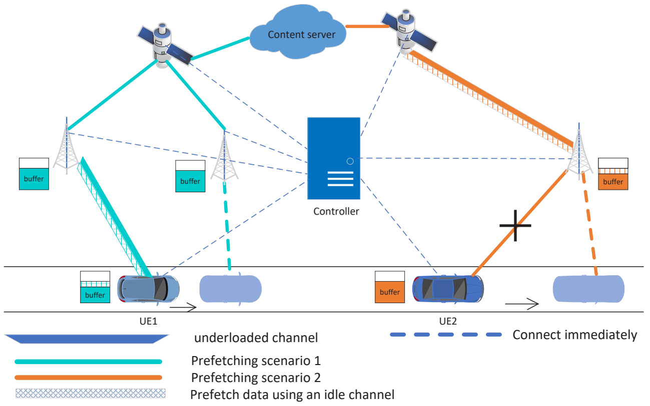

Fig. 1: Scenario description

Section V.

## II. SYSTEM MODEL

### A. Network Model

In this paper, we consider the downlink in the network, which consists of a set $\mathcal{J}$ access nodes(ANs), a set $\mathcal{I}$ users, and a set $\mathcal{K}$ satellites. $x_{ij} = 1$ denotes user $i$ is associated with AN $j$; otherwise $x_{ij} = 0$. ANs are connected to the core network via the satellites $\mathcal{K}$ as a backhaul link.Similarly, $\eta_{jk} = 1$ indicates that AN $j$ is associated with LEO $k$; otherwise $\eta_{jk} = 0$. $r^a_{ij}$ and $r^b_{ijk}$ are the data rates of users on the wireless links and the backhaul links respectively. The satellite $k$ provides the ANs with $O_k$ total backhaul bandwidth. $\lambda_{ij}$ denotes the spectral efficiency of the AN $j$ and the user $i$. The same to spectral efficiency parameters $\eta_{jk}$ between the satellite $k$ and AN $j$ without considering small-scale fading (e.g., frequency-selective fading), by using Shannon bound, the average UE $i$'s SE $\lambda_{ij}$ (bps/Hz) over the scheduling interval is calculated as $\lambda_{ij} = log(1 + g_{ij}p_{ij}/\sigma_0)$. The fixed equal power allocation mechanism is used, which means transmission power $p_{ij}$ is the same for all frequencies. $\sigma_0$ is the power spectrum density of additive white Gaussian noise. Similarly, we can figure out $\eta_{jk}$.

To implement adaptive prefetch on terminals and ANs, traffic should have two types of caches, one on the terminals and the other on ANs. $m_i$ and $v_{ij}$ represents the cache of user $i$ and the cache of user $i$ at AN $j$. The maximum cache spaces of UE $i$ and AN $j$ are denoted by $M_i$ and $V_j$.

To avoid cache exhaustion, we require the user cache data to be at least $\overline{m}_i$, and the base station cache data to be at least $\overline{v}_i$. To ensure a good cache state, it is necessary to predict the state of the network at the next moment, including the channel conditions of the wireless access channels and backhaul links and the corresponding data transmission rate. The rates of wireless access links and backhaul links at the next moment are represented by $r^{a,T}_{ij}$ and $r^{b,T}_{ijk}$.

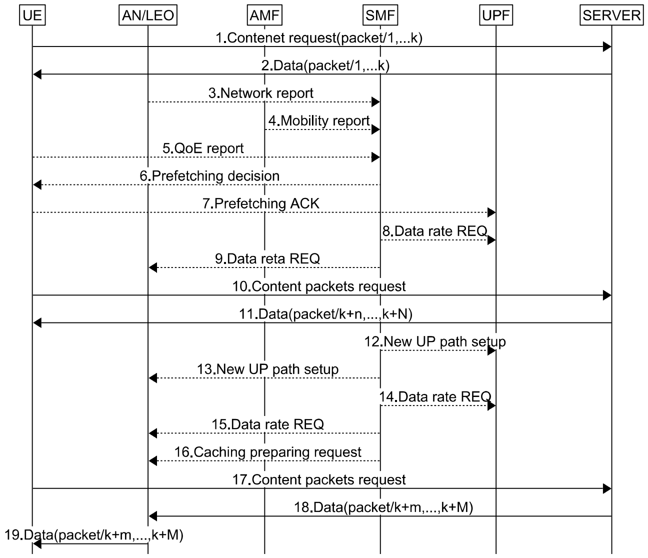

Fig. 2: Message exchange for supporting the adaptive prefetching.

### B. Adaptive Prefetch Protocol

To implement the adaptive prefetch strategy, we must design a good signaling protocol. It is important to note that we only give an example, but different protocols are definitely needed for different services.

As shown in Fig.2, the Access and Mobility Management Function (AMF) manages the mobility and access of users. It contains the mobility context of users. Thus, AMF can obtain the user's location information. Session Management Function (SMF), is a core network (CN) function entity as well that manages and monitors services (PDU sessions) of the network [9]. In the adaptive prefetching, the SMF tries to optimize the QoE of UEs by taking into consideration of the QoE report from UEs and the predicted network information from the AMF. In Fig.2, we divide the stage before sending the prefetch data into two parts which are the prefetch preparation stage and the prefetching request stage. In the part of prefetch preparation, the users, ANs, LEOs, and AMF send relevant information to the SMF. (e.g.the buffer size of users, the bandwidth of ANs and LEOs, the location of users, ANs and LEOs), For the SMF to decide whether to prefetch or not at this time, the future data rate should be transmitted to SMF. In the part of the prefetching request, SMF sends prefetch requests to the relevant users who may need prefetching. If the users accept prefetching requests, they will send Acknowledgement (ACK) back to SMF according to the received information, otherwise, the users will send negative-Acknowledgement (NACK) to SMF. If the SMF receives ACK signal, it will inform the relevant ANs and LEOs to adjust the flows that will carry the prefetching data. Both ANs and LEOs will allocate additional bandwidth to transmit more data. The SMF will also inform ANs to allocate additional buffer space for prefetched data to keep the data in cache space longer. If other ANs are involved, new UP paths may need to be set up.

## III. PROPOSED OPTIMIZATION PROBLEM AND METHOD

In this section, the optimization problem of the maximum wireless access rate based on fairness is proposed under the constraints of bandwidth and cache space.

*1) Objective::* To keep the user cache from being exhausted, it is reasonable to maximize the wireless access rate based on the log function under the condition of ensuring proportional fairness(PF). The specific formula is as follows:

$$U = \sum_{\substack{i \in I \\ j \in J}} x_{ij} \log\left(r_{ij}^{a}\right) + \sum_{\substack{i \in I \\ j \in J}} x_{ij}^{T} \log\left(r_{ij}^{a,T}\right) \tag{1}$$

The first half is the user's wireless access rate at the current moment (from $t$ to $t+T$), and the second half is the predicted wireless access rate at the next moment (from $t+T$ to $t+2T$). Maximizing the rate at the two moments can effectively reduce the impact of unknown channel conditions. $x_{ij}^{T}$ denotes the predicted association between user $i$ and AN $j$ at the next moment.

*2) Constraints::* To enable users to watch videos smoothly, the network needs to ensure that the cached data of users is above the threshold before the start of the next time slot. In this network, we only need to ensure that the cached data of users is above the threshold after two-time slots because the network can predict the network status of the next time slot, which can be expressed as:

$$m_i^0 + \sum_{j \in J} x_{ij} r_{ij}^{a} T + \sum_{j \in J} x_{ij}^{T} r_{i}^{a,T} T - C_i \geq \bar{m}_i, \forall i \tag{2}$$

$m_i^0$ denotes the existing cache of user $i$ at time $t$, and $C_i$ is the data consumed by user $i$ from $t$ to $t+2T$. When the user is in a region that cannot connect to ANs, the user does not need to satisfy this constraint. Similarly, to avoid freezing the transmission flow from AN $j$ to user $i$, the data of user $i$ cached in AN $j$ should also be kept above threshold $\bar{v}_{ij}$. The constraint at AN $j$ should be:

$$v_{ij}^{0} + R_1 - R_2 \geq x_{ij}^{T} \bar{v}_{ij}, \forall i, j \tag{3}$$

$v_{ij}^{0}$ is the existing cache for user $i$ on AN $j$. To facilitate expression, we use $R_1 = x_{ij}\eta_{jk} r_{ijk}^{b} T + x_{ij}^{T} \eta_{jk} r_{ijk}^{b} T + x_{ij}^{T} \eta_{jk}^{T} r_{ijk}^{b,T} T$ and $R_2 = x_{ij} r_{ij}^{a} T + x_{ij}^{T} r_{ij}^{a,T} T$ to represent the data transmitted to AN $j$ and user $i$ .Note that when $x_{ij}^{T} = 0$, $x_{ij}^{T}\bar{v}_{ij} = 0$, which means that when the system predicts that user $i$ is not associated with AN $j$ at the next moment, AN $j$ does not need to keep the data of user $i$ above the threshold, so it can provide more cache space for other users and improve the utilization rate of cache space.

In addition to threshold constraints, cached data should also be constrained by the size of cache space, as shown in Eq.(4) and Eq.(5):

$$\sum_{j \in J} x_{ij} r_{ij}^{a} T + \sum_{j \in J} x_{ij}^{T} r_{ij}^{a,T} T - C_i \leq M_i, \forall i \tag{4}$$

$M_i$ denotes cache space of user $i$. Similarly, limited by the size of the base station cache space is as follows:

$$\sum_{i \in I} \left(v_{ij}^{0} + R_1 - R_2\right) \leq V_j, \forall j \tag{5}$$

In addition to prediction-based cache constraints, there should also be current time-based cache constraints:

$$\sum_{i \in I} v_{ij}^{0} + x_{ij}\eta_{jk} r_{ijk}^{b} T + x_{ij}^{T}\eta_{jk} r_{ijk}^{b} T - x_{ij} r_{ij}^{a} T \leq V_j, \forall j \tag{6}$$

and

$$v_{ij}^{0} + x_{ij}\eta_{jk} r_{ij}^{b} T + x_{ij}^{T}\eta_{jk} r_{ijk}^{b} T - x_{ij} r_{ij}^{a} T \geq 0, \forall i, j \tag{7}$$

$C_i'$ denotes the data consumed by user $i$ from $t$ to $t+T$. Bandwidth resource constraints of backhaul links and wireless access links are as follows:

$$\sum_{i \in I} x_{ij} r_{ij}^{a} / \lambda_{ij} \leq W_j, \forall j \tag{8a}$$

$$\sum_{i \in I} x_{ij}^{T} r_{ij}^{a,T} / \lambda_{ij}^{T} \leq W_j, \forall j \tag{8b}$$

and

$$\sum_{j \in J} \sum_{i \in I} \left(x_{ij}\eta_{jk} r_{ijk}^{b} + x_{ij}^{T}\eta_{jk} r_{ijk}^{b}\right) \Big/ \eta_{ij} \leq O_k, \forall k \tag{9a}$$

$$\sum_{j \in J} \sum_{i \in I} \left(x_{ij}^{T}\eta_{jk}^{T} r_{ijk}^{b,T}\right) \Big/ \eta_{ij}^{T} \leq O_k, \forall k \tag{9b}$$

Combining the above constraints we can give the original problem **P0** from the adaptive problem:

$$\begin{aligned} \max_{\mathcal{X},\mathcal{R}} \quad & U \\ s.t. \quad C1: \quad & \sum_{j \in J} x_{ij} \leq 1, \quad \sum_{j \in J} x_{ij}^{T} \leq 1, \forall i \\ C2: \quad & (2) - (9) \\ C3: \quad & r_i^{a}, r_{ij}^{a,T}, r_{ijk}^{b}, r_{ijk}^{b,T} \in \mathbb{R}^{+} \\ & x_{ij}, x_{ij}^{T} \in \{0,1\}, \forall i, j \end{aligned} \tag{10}$$

It is worth noting that the correlation between AN and satellite is not within the scope of consideration in this letter and we assume that any AN is served by the LEO that provides the best spectrum efficiency (SE).

### *A. Problem Transformation*

The existence of binary variables $x_{ij}$, $x_{ij}^{T}$ and the product of variables causes problem P0 to be a non-convex problem, and therefore, in this subsection, the problem is converted to convex by relaxation and substitutions of variables.

We relax $x_{ij}, x_{ij}^{T} \in \{0,1\}$ to $x_{ij}, x_{ij}^{T} \in [0,1]$. Relaxed $x_{ij}$ and $x_{ij}^{T}$ can be interpreted as the time sharing factors that represent the ratios of time when UE $i$ associates to BS $j$ [10]. To deal with the product relationship between correlation variables and link rates. We made the corresponding substitution shown as $x_{ij} r_{ij}^{a} = \dot{r}_{ij}^{a}$, $x_{ij}^{T} r_{ij}^{a,T} = \dot{r}_{ij}^{a,T}$, $x_{ij}\eta_{jk} r_{ijk}^{b} = \dot{r}_{ijk}^{b}$, $x_{ij}^{T}\eta_{jk} r_{ijk}^{b} = \ddot{r}_{ijk}^{b}$, and $x_{ij}^{T}\eta_{jk}^{T} r_{ijk}^{b,T} = \dot{r}_{ijk}^{b,T}$, the objective function is then presented as:

$$U = \sum_{\substack{i\in I\\ j\in J}} x_{ij} \log\left(\frac{\dot{r}^{a}_{ij}}{x_{ij}}\right) + \sum_{\substack{i\in I\\ j\in J}} x^{T}_{ij} \log\left(\frac{\dot{r}^{a,T}_{ij}}{x^{T}_{ij}}\right) \tag{11}$$

To avoid meaningless results, we specify $x_{ij}\log\left(\dot{r}^{a}_{ij}/x_{ij}\right), x^{T}_{ij}\log\left(\dot{r}^{a,T}_{ij}/x^{T}_{ij}\right) = 0$ when $x_{ij}, x^{T}_{ij} = 0$. Accordingly, the variables of the constraint change, and finally problem **P0** becomes :

$$\begin{aligned} \max_{\mathcal{X},\mathcal{R}} \quad & U \\ s.t. \quad & C1, \dot{C}2 : (\dot{2}) - (\dot{9}) \\ & \dot{C}3 : \dot{r}^{a}_{ij}, \dot{r}^{a,T}_{ij}, \ddot{r}^{b}_{ijk}, \dot{r}^{b}_{ijk}, \dot{r}^{b,T}_{ijk} \in \mathbb{R}^{+} \\ & \quad x_{ij}, x^{T}_{ij} \in [0,1], \forall i, j \end{aligned} \tag{12}$$

**Proposition 1:** After substitution, problem (12) is equivalent to the original problem after relaxation.

**Proof:** This proof of Proposition 1 is motivated by [11]. The variables of problem10 can be easily recovered, except The denominator is zero. Due to this situation, it is not a one-to-one mapping between the variables of the two problems. However, if $x_{ij} = 0$, that is, user $i$ is not connected to AN $j$, because of optimality, The system will not allocate resources to them. In other words, $r^{a}_{ij} = 0$.Similarly, we can get the corresponding values of other special points. It can be expressed as :

$$r^{a}_{ij} = \begin{cases} \dfrac{\dot{r}^{a}_{ij}}{x_{ij}} & x_{ij} \neq 0 \\ 0 & x_{ij} = 0 \end{cases}, r^{a,T}_{ij} = \begin{cases} \dfrac{\dot{r}^{a,T}_{ij}}{x^{T}_{ij}} & x^{T}_{ij} \neq 0 \\ 0 & x^{T}_{ij} = 0 \end{cases} \tag{13}$$

$$r^{b}_{ijk} = \begin{cases} \dfrac{\dot{r}^{b}_{ijk} + \ddot{r}^{b}_{ijk}}{(x_{ij} + x^{T}_{ij})\eta_{jk}}, & o.w. \\ 0, & x_{ij} + x^{T}_{ij} = 0 \, or \, \eta_{ij} = 0 \end{cases} \tag{14}$$

$$r^{b,T}_{ijk} = \begin{cases} \dfrac{\dot{r}^{b,T}_{ijk}}{x^{T}_{ij}\eta_{jk,T}}, & o.w. \\ 0, & x_{ij} = 0 \, or \, \eta^{T}_{jk} = 0 \end{cases} \tag{15}$$

$(2) - (9)$ is converted to $(\dot{2}) - (\dot{9})$ by substitution.Due to the limited space, there is no more detailed process of substitutions. At this time, the objective function becomes convex about $x_{ij}, x^{T}_{ij}, r^{a}_{ij}$ and $r^{a,T}_{ij}$, and the constraints are linear constraints, so the original problem is transformed from non-convex to convex. There are many ways to solve this problem. In this letter. We introduce logarithmic barrier functions into the original problem, and then solve the problem by the Newton method, as shown in Alg.1.

$f(x)$ in Alg.1 is the sum of the utility function and the logarithmic barrier function:

$$f(x) = U + \sum_{i=1}^{m} 1/(t)\log\left(-h_i(x)\right) \tag{16}$$

$h(x)$ are the constraints in the original problem.

**Algorithm 1** Maximize prefetching benefit Algorithm

```
Initialization
Given Initial point  $\mathcal{X} \in dom f$,error threshold  $\epsilon > 0$
repeat Main Loop
Calculate Newton step size and decrement
$\Delta x_{nt} := -\nabla^2 f(x)^{-1}\nabla f(x)$
$\lambda^2 := \nabla f(x)^T \nabla^2 f(x)^{-1} \nabla f(x)$
if $\lambda^2/2 \leq \epsilon$ then
    Return  $\mathcal{X}$
else
    determining Step $t$ by backtracking line search
end if
update $x := x + t\Delta x_{nt}$.
```

### *B. Binary Variables Recovery*

To transform the original problem(10) into the convex problem, we relax the binary variables $x_{ij}$ and $x^{T}_{ij}$ to continuous variables. Therefore, it is necessary to recover the $x_{ij}$ and $x^{T}_{ij}$ in the solution of the relaxed problem the $x_{ij}$ and $x^{T}_{ij}$ to the original binary variables. We adopt Algorithm 2 to recover the binary variables in the problem. Let's take $x_{ij}$ as an example and apply the same algorithm to $x^{T}_{ij}$ to get the actual values. $\mathcal{L}$ is the Lagrange operator of the original problem.

**Algorithm 2** Binary Variables Recovery

```
Computing first partial derivations
Compute the first partial derivations of augmented Lagrangian $Q_{ij} = \partial L/\partial x_{ij}$
Sort all the partial derivations $Q_{ij}, \forall i, j$ from largest to smallest. Mark them with $Q_1, Q_2 ... Q_i, ...$and mark the corresponding $x_{ij}$ as $x_1$,$x_2$,...$x_i, ...$
for $i = 1, 2, ...$ do
    Set $x_i = 1$ and $x_{i+1}, x_{i+2}, x_{i+3}, ... = 0$
    if Any of the constrains (10) C1-C3 does not hold,Then Break
end for
output the recovered binary variables
```

## IV. SIMULATION RESULTS

The proposed adaptive prefetching scheme is evaluated by simulation. In this simulation, we consider a highway scenario with 120 users, 10 base stations, and 10 satellites. The users moves forward at the speed of 15m/s on the expressway, and the satellites moves at the speed of 6000m/s. In the scene, we set up the strong fading area of the wireless access links and backhaul links respectively, to see the system brought by the adaptive cache strategy more obviously. The video-consuming bandwidth ranges from [1, 3] Mbps. The remaining simulation setups are listed in TableI.

The three curves in Fig.3 show the change of average user stalling ratio with the increase of base station caches under different user caches. It can be seen that when the size of the

TABLE I: Simulation Parameters

| Parameters | Value |
|---|---|
| Number of users | 60 |
| Number of BSs | 10 |
| Number of LEOs | 10 |
| BS distribution | 1-D Line,randomly W |
| Bandwidth of satellites($O$) | 50 MHz |
| Bandwidth of BSs($O$) | 20 MHz |
| Minimum Inter-BS distance | 250 m |
| Average Inter-BS distance | 500 m |
| Transmission power | 46 dBm |
| Average video rate | 2 Mbps |
| Video rate distribution | Gaussian |
| Simulation Length | 200 s |
| Predicted cycle length | 1 s |
| Maximum prefeching buffer of users | [2,5,10,20] s |
| Maximum prefeching buffer of BSs | [2,5,10,20] s |

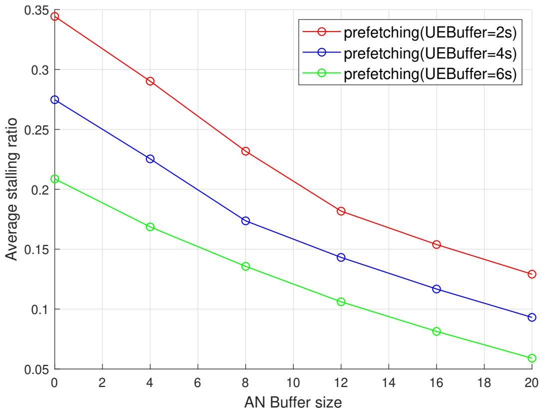

Fig. 3: Average stalling ratio of different AN buffer

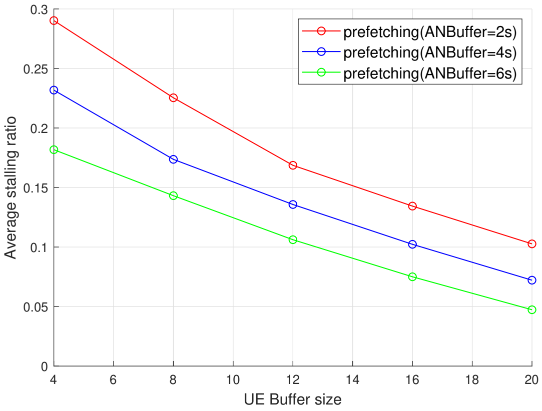

Fig. 4: Average stalling ratio of different UE buffer

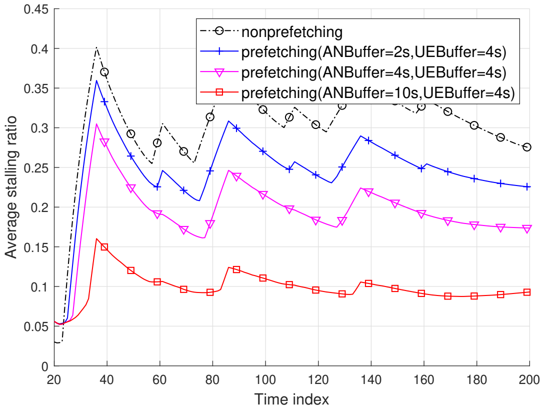

Fig. 5: Average stalling ratio over time of different AN buffer

base station cache increases, the average user loss rate becomes lower and lower, which means that users can get a smoother viewing experience. It should be noted that with the increase of AN buffer, the decreasing trend of the average stalling ratio becomes lower and lower, meaning that the average stalling ratio will not decrease indefinitely with the increase of the base station cache. Similarly, Fig.4 indicates that the average stalling ratio decreases with the increase of UE buffer when AN buffer is fixed.

Fig.5 illustrates the change of average user stalling ratio over time during the whole simulation process. Fig.6 compared the difference between the adaptive prefetching mechanism and the non-adaptive prefetching mechanism, and with the increase of AN buffer, the average stalling ratio of users showed a downward trend during the whole simulation process. To verify the improvement brought by the AN buffer to the network when the backhaul link is not ideal, we set up some areas where the backhaul link is greatly fading in the simulation, which corresponds to the position where the change range in the figure is relatively large. It is found that when the base station can buffer the video for 20 seconds, the fluctuation of this part is small, indicating that the scheme effectively compensates for the unsatisfactory backhaul link.

## V. CONCLUSION

In this paper, an adaptive prefetching mechanism based on the satellite network and SDN was proposed. To implement this adaptive scheme, a system and method were proposed to retrieve users' data to the corresponding ANs or UEs prior to making the actual request. The simulation results have shown that this mechanism can effectively compensate for the link fluctuation of wireless and backhaul links and improve user experience as well as bandwidth utilization. We will consider the enhancement of edge caching and edge computing on satellites in the future.

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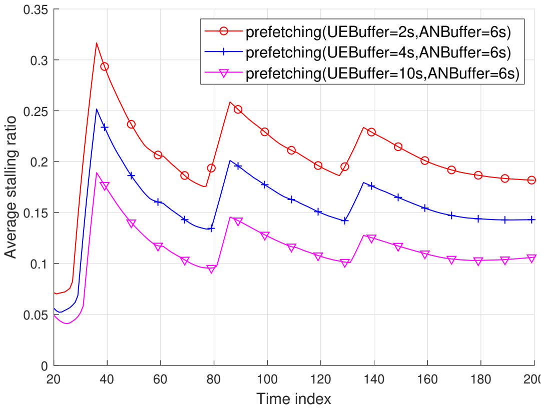

Fig. 6: Average stalling ratio over time of different UE buffer

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