Evaluation of Time Dimensional Traffic Engineering with Storage Aware Routing

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***Abstract*—Recently, the amount of traffic on the Internet continues to grow by increment of rich content such as video every year. Not only the overall traffic increase but also the time variation becomes large and the difference in the amount of traffic during the time of peak and off peak is very large. Therefore, it is difficult to use the link bandwidth efficiently. In this paper, we propose a new system of content distribution, named Storage Aware Routing (SAR). With SAR, routers can exploit the links with low utilization by using their large storages. Our performance evaluation of SAR by binary integer programming formulation shows that SAR is able to smooth the link utilization.**

Keywords-Storage; Content Distribution; New Generation Network; Traffic Peak Shift.

I. INTRODUCTION

Traffic volume transferred in the Internet has been steadily increasing with continuous growth of video traffic. According to Cisco white paper [1], it increases eight-fold in 5 years and will be approaching 1.3 zeta byte by the end of 2016. Sophisticated network management is indispensable for effective accommodation of increasing traffic demand. Content Delivery Network (CDN) [2] and traffic engineering [3] are promising examples for effective network management. These techniques aim to distribute traffic in space dimension by adequate routing. This means traffic can be managed only in space dimension in these conventional techniques.

Another impact of current Internet traffic than traffic volume is the difference between peak and minimum traffic volume in day-time scale. According to Japanese government report [4], difference between peak and minimum traffic in day-time scale significantly increases recently. In the conventional traffic management technique, bandwidth of the most congested link should be designed to accommodate peak traffic. Average link utilization should be small due to bursty nature of traffic, which means network resources cannot be effectively utilized only with spatial traffic management techniques.

Large storage can be used for time dimensional traffic management. While the network is congested, traffic stored in a network, i.e., at routers, can be transmitted during off-peak time period. Delay Tolerant Network (DTN) [5] is one example of usage of storage for traffic shift. It enables asynchronous forwarding, but its main purpose is providing reliable communications between a wide range of networks having poor and disparate performance, which means DTN is not a technology for traffic management. Some methods that control the timing of transmission with nodes' storage are proposed [6] [7]. Because these methods do not consider deadline of delivered data, they cannot guarantee the arrival of priority data in time. Another method of asynchronous forwarding is also proposed for inter-datacenter bulk transfer, called NetStitcher [8]. In NetStitcher, bulk data transfer is scheduled to adapt to resource fluctuation in diurnal pattern. NetStitcher is applied for world wide datacenter systems and bulk transfer is scheduled so that off-peak in diurnal fluctuation is to be used. Purpose of NetStitcher is very similar to ours, traffic management in time dimension, but it can only be applied to worldwide scale datacenter systems because it adapts to resource fluctuation due to local time difference.

In near future, new usage scenario of video services can be deadline-aware, such as a user reserves her preferable video services with her convenient time. One promising scenario for this deadline-aware video service is that in the morning a user on a commuter train reserves video service with evening time on which she can enjoy it at her home. In current video on demand, e.g., YouTube, peak traffic period is exactly the peak demand time period and may be prime time in the evening. In contrast, in deadline-aware video service, there is time leeway for receiver to receive content (video) file. Another example of deadline-aware delivery is backup of critical data between distant data centers for Business Continuity Planning (BCP). When a router has large storage space and can storage content traffic in the case of the following link is in its peak traffic period, on-peak traffic can be shifted to off-peak period.

In this paper, we propose a novel traffic engineering technique which manages traffic in not only space but also time dimension, SAR. SAR is one of traffic engineering technique and aims at adapting to link utilization fluctuation. In SAR, a router stores content traffic at its storage and time-shifts on-peak traffic to off-peak time period. Storage at a router is assumed to be large enough to enable time-shift of on-peak traffic, i.e., plentifully large storage than

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current router queue. In this paper, we formulate SAR traffic management as time-space dimension routing problem. With numerical examples binary integer programming problem for time-space dimension model, we comparatively evaluate SAR. Our numerical examples show that SAR can effectively adapt to fluctuation of link utilization. And we investigate condition that SAR can work well and show that SAR generally works well. In this paper, we investigate the feasibility and the fundamental benefits of deadline-aware content delivery with SAR.

This paper is structured as follows. First, in Section 2, we explain our proposed new traffic engineering technique, named SAR, in detail. In Section 3, we evaluate performance of SAR by using binary integer programming. Finally, we conclude a paper in Section 4.

II. STORAGE AWARE ROUTING

A. Design Concept of SAR

In the current Internet, sharp increase of content traffic volume is one of the most important technical issues. Especially, difference between peak and off-peak traffic volume is significantly increasing. When some content traffic on peak period can be shifted to off-peak time period, smoothed content traffic volume will enable effective accommodation of increasing content traffic. So, we propose Storage Aware Routing which enables time-dimensional traffic shift for deadline-aware content distribution.

An end-user is interested only in content itself. She does not care about content retrieval time and content can be retrieved anytime before her preferable time to watch it. SAR tactically utilizes time difference between reserved timing and content watching timing. According to the above mentioned content retrieval nature, content can be retrieved between these two timings. In SAR, each session (end-to-end session for one content retrieval) schedules its hop-by-hop transmission timing so that fluctuation of link utilization along transmission path is minimized. With this smoothed link utilization, network can reserve its resources to sessions generated later.

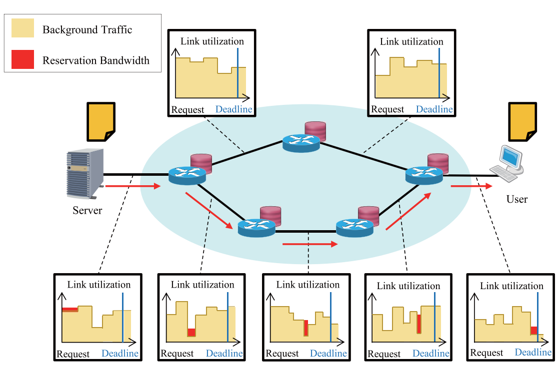

Figure 1. Storage Aware Routing

B. Storage Aware Routing

Fig. 1 shows overview of SAR. Framework of SAR is composed of the following 3 elements.

1) Reservation by end user
2) Scheduling of transmission at the server
3) Routing and scheduling in the network

SAR is time dimensional traffic engineering technique by making use of time difference between reservation and content watching. At an end-user side, reservation for content is a trigger to SAR (reservation by end user). A server and networks schedule transmission timings of a corresponding content file so that fluctuation of link utilization is minimized. A server decides its transmission timing (scheduling of transmission at the server). A network decides a path for content file transmission and schedules hop-by-hop transmission timing (routing and scheduling in the network).

In Fig. 1, SAR chooses route and transmission timing which enables low link utilization. A graph for each link depicts link utilization variance in time. SAR first chooses a route enabling low link utilization. Then SAR schedules hop-by-hop transmission timing. On the first link in Fig. 1, content file is not transferred in the lowest utilization time period. This is because of law of causality for low utilization periods on the following links. When content file is transferred in the lowest utilization time period on the first link, content must be transferred in high utilization time period of the following link so as to reach before deadline. SAR designs not only routing but also transmission timing at each hop on the route, i.e., routing and scheduling.

III. NUMERICAL EXAMPLES

One of the most advanced aspects of SAR is time dimensional scheduling enabled by large storage at a router. In this paper, basic performance of SAR in this aspect is evaluated by numerical examples with binary integer programming formulation.

A. Problem Formulation of SAR

SAR design can be formulated as a routing problem in space-time diagram. Fig. 3 shows space time diagram for the tandem topology model shown in Fig. 2. Horizontal axis shows time dimension and vertical axis shows space dimension. Space dimension corresponds to tandem network shown in Fig. 2. The origin ($[S][T]=00$) of this time space diagram shows the content server at time 0. Time is normalized with file transmission time on a link (we simply assume that a content file is transmitted on a link in 1 time unit). In a sample path in Fig. 3, the server transmit content file to router 1 at time 0. Router 1 does not store it and forwards it to router 2 immediately after it receives a whole file at time 1. At routers 2 and 3, content file is stored during one unit time, which is time dimensional scheduling. In this example, deadline of content retrieval is time 8 and a content file is retrieved just at this deadline.

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Figure 2. Tandem topology model

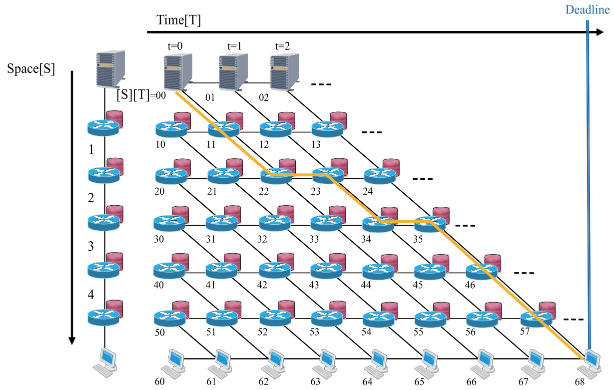

Figure 3. Space-time diagram

SAR design can be formalized as the following minimization of total cost for a "path" in space time diagram. In our design, we set the link cost to the square of utilization to smooth the traffic in the networks. We set the cost of storage to 0 supposing that storage capacity is very large. The impact on other cost functions will be studied in future.

$$minimize \sum_{(i,j)\in E, t\in T} COST_{i,j,t} * X_{i,j,t} + \sum_{i\in V, t\in T} COST_{i,i,t} * X_{i,i,t} \quad (1)$$

$subject \quad to$

$$BT_{i,i,t} + d * X_{i,i,t} \leq C_{i,i} \quad (2)$$

$$BT_{i,j,t} + d * X_{i,j,t} \leq C_{i,j} \quad (i \neq j) \quad (3)$$

$$\sum_{j:(i,j)\in E, t\in T} X_{i,j,t} + \sum_{i\in V, t\in T} X_{i,i,t} - \sum_{j:(j,i)\in E, t\in T} X_{j,i,t-\Delta t} - \sum_{i\in V, t\in T} X_{i,i,t-\Delta t} = 0 \quad (i_t \neq s, r) \quad (4)$$

$$\sum_{j:(s,j)\in E, R\in T} X_{s,j,R} + \sum_{tr\in T} X_{s,s,R} - \sum_{j:(j,s)\in E, R\in T} X_{j,s,R-\Delta t} - \sum_{tr\in T} X_{s,s,R-\Delta t} = 1 \quad (i_R = s) \quad (5)$$

$$\sum_{j:(r,j)\in E, D\in T} X_{j,r,D-\Delta t} + \sum_{D\in T} X_{r,r,D-\Delta t} - \sum_{j:(j,r)\in E, D\in T} X_{r,j,D} - \sum_{D\in T} X_{r,r,D} = 1 \quad (i_D = r) \quad (6)$$

$$COST_{i,j,t} = ((BT_{i,j,t} + d)/C_{i,j})^2 \quad (i \neq j) \quad (7)$$

$$COST_{i,i,t} = 0 \quad (8)$$

TABLE I
NOTATION USED IN THE PAPER

Notation	Meaning
$X_{i,j,t}$	- Binary variable denoting reservation of link (i, j) $(for \quad i \neq j)$ - Binary variable denoting reservation of storage at router i $(for \quad i = j)$ for time period between t and $t + \Delta t$
$COST_{i,j,t}$	- Transmission cost on link (i, j) $(for \quad i \neq j)$ - Storage cost at node i $(for \quad i = j)$ for time period between t and $t + \Delta t$
$BT_{i,j,t}$	- Background traffic volume of link (i, j) $(for \quad i \neq j)$ - Stored background traffic volume at router i $(for \quad i = j)$ for time period between t and $t + \Delta t$
$C_{i,j}$	- Link capacity of link (i, j) $(for \quad i \neq j)$ - Storage capacity of router i $(for \quad i = j)$
d	Traffic demand for each session
E	Set of links
V	Set of nodes
T	Set of discrete time periods (denoting each time unit)
s	Currently requesting sender
r	The receiver at the corresponding deadline in time-space diagram
i_t	Router i at time t in time-space diagram
D	Corresponding deadline
R	Generation time of request for the currently focused traffic

Table I shows the notations used in this paper. Equation (1) shows the objective function of SAR. The first term is summation of cost for file transfer on link (i, j) along the space dimensional path (set of diagonal lines on time space diagram path). The second term is summation of storage cost at routers (set of horizontal lines on time space diagram path). So, the objective function of SAR aims for minimizing accumulation of link cost and storage cost. Link cost should have close relationship with link utilization, i.e., link cost should be large for high link utilization. Equations (2) and (3) give capacity constraint for storage and link, respectively. The first term of each equation gives accumulated link and storage usage for background traffic. The second term shows link and storage usage offered by currently reserved session. So, when (2) and (3) are satisfied, newly reserved traffic can be accommodated without overutilization. Equation (4) gives session conservation at each transient node. It means that the traffic coming into a node between $t-\Delta t$ and t must be equal to the traffic going out between t and $t + \Delta t$ for any node except requesting node and the receiver node. Equations (5) and (6) show session conservation at the requesting time of the sender and the deadline for the corresponding session, respectively. They mean that the traffic must go out from the currently requesting sender node at the requesting time and come into the receiver node at the corresponding deadline. The cost of link and storage are defined as (7) and (8), respectively.

Because we investigate fundamental effectiveness of traffic smoothing with SAR, we assume that storage capacity is enough large and much cheaper than link cost. Therefore, we set storage cost as 0 in this evaluation. It is possible to consider storages capacity limitation with defining cost function for the storage as link cost. We use binary integer

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TABLE II
NOTATION USED IN ALGORITHM

Notation	Meaning
scr	Sender node of content
dst	Receiver node of content
dl	Deadline time of content distribution
G	Graph of network topology
G'	Time-space diagram for G
E'	Set of links in G'
unit_size	Chunk size that can be sent in unit time
$src(rqtime)$	Src at request time
$dst(dl)$	Dst at deadline time
P	Shortest path from $src(rqtime)$ to $dst(dl)$ in G'

programming for fundamental evaluation. It is also possible to use Dijkstra's algorithm to calculate shortest path in space-time diagram. Route calculation algorithm of SAR is shown in Algorithm 1. Notations used in Algorithm 1 are shown in Table II. This system assumes that link capacity in future can be reserved. We suppose to use centralized controller such as OpenFlow [9]. Centralized controller has a potential to manage link bandwidths in the network and to dictate scheduled transmission timing to routers.

Algorithm 1 Route calculation algorithm in SAR

$Calc\_SAR\_Route\ (G, src, dst, dl, size)$
  $G' = ExtractGraphToTimeDimension\ (G, src, dst, dl)$
  $SetCost\ (l\ in\ E')$
  $m = content\_size\ /\ unit\_size$
  for i = 1 to m **do**
    $P = CalcShortestPath\ (G', src(rqtime), dst(dl))$
    $UpdateCost\ (l\ in\ P)$
  end for

B. Basic Performance

In this section, we evaluate SAR with simple tandem model with 5 routers (see Fig. 2). In this model, background traffic is artificially given as normal distribution with mean of 40 and standard deviation of 10. Capacity of each link is 100. Link usage of each session is simply given by fixed value 3.

SAR is comparatively evaluated with the following two design policies.

1. SAR-edge

   In SAR-edge, the sender, i.e., the content server, can schedule its transmission time so as to minimize total cost of link and storage on the path. In SAR, all routers on the path can store content file but in SAR-edge, only edge router can store content file.

2. Fastest Reservation (FR)

   At request generation timing, transmission of content file is scheduled as fast as possible on condition that link usage of scheduled traffic is up to link capacity.

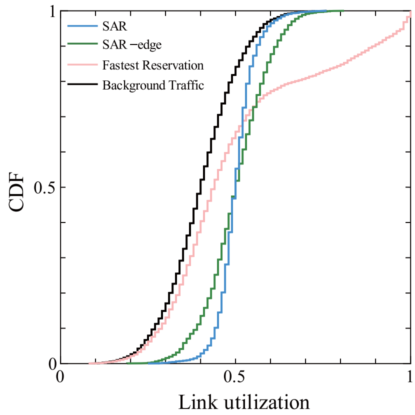

Figure 4. CDF of unit-time link utilization

Fig. 4 shows CDF of unit-time link utilization of SAR, SAR-edge and FR. CDF of background traffic is also shown in this figure.

In FR, large portion of content file transmission is scheduled at high link utilization time period. SAR-edge has smoothed link utilization distribution than FR, which means only with the sender scheduling smoothing of link utilization can be realized on some level. With scheduling of the router storage, SAR has more smoothed link utilization and has the best characteristics among three. As shown in this result, time dimensional scheduling enabled by large storage at a router has great effect on smoothing link utilization.

C. Accumulated Session Model

1) Link utilization smoothing effect of SAR: In this section, we evaluate SAR in more sophisticated model, accumulated session model. Fig. 5 shows mesh model with 5 senders, 5 receivers and 5 tandem routers. Sessions are set up for 5 server-receiver pairs of (a, j) (b, f), (c, g), (d, h) and (e, i). The latter 4 pairs generate the following traffic before the first pair so that generated traffic of these 4 pairs is background traffic for the first pair. At first, 1200 sessions (300 sessions for each pair) with short allowable reservation time (rather short time interval between request generation time and deadline) are generated for the latter 4 pairs. Their request generation is normally distributed with mean value denoted in Table III and standard deviation of 7.5. In pattern a, server e has the earliest generation mean time of its request and the latest one in pattern b. Mean deadline value

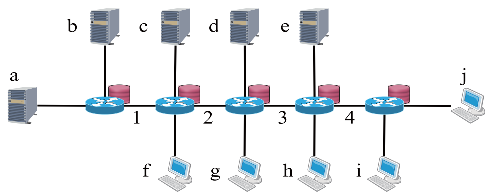

Figure 5. Mesh model

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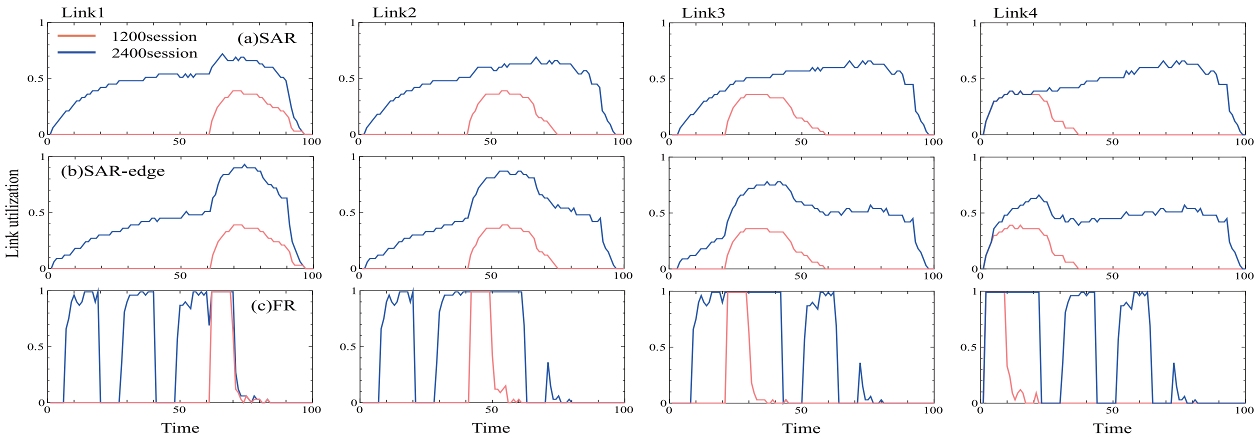

Figure 6. Link utilization - pattern *a*

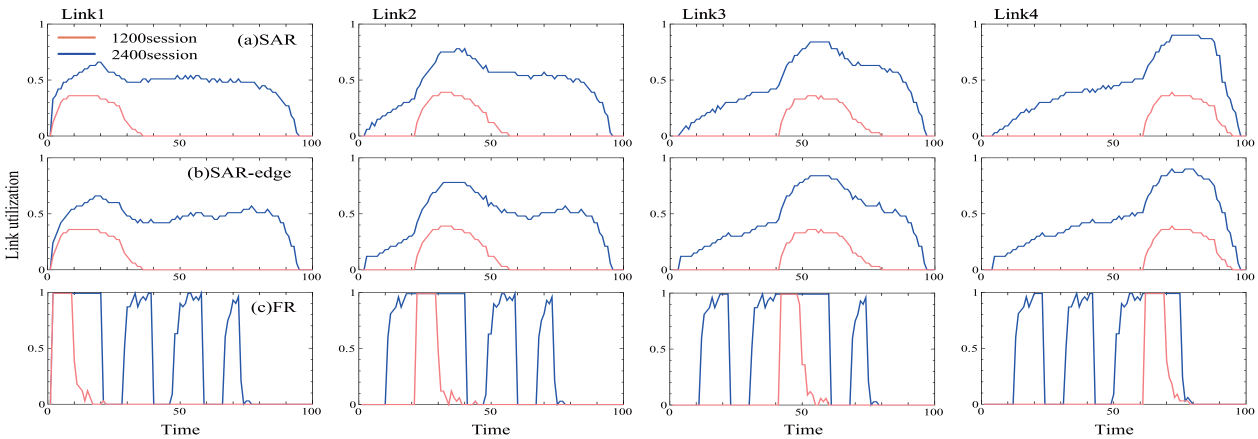

Figure 7. Link utilization - pattern *b*

is exponentially distributed with 20 unit time later than mean generation time, e.g., server e has mean deadline of 40 in pattern a. With these assumptions, background traffic has average 20 unit time allowance for its reservation.

TABLE III
MEAN VALUE OF NORMAL DISTRIBUTION

server-receiver pair	pattern a mean value	pattern b mean value
$b-f$	80	20
$c-g$	60	40
$d-h$	40	60
$e-i$	20	80

After these generations of background traffic, Node j starts reservation to Server a for its generated 1200 sessions. Deadline of these 1200 sessions is normally distributed with mean 80 and standard deviation of 7.5. Request generation time is exponentially distributed between 0 and deadline assigned by the above described normal distribution. Figs. 6 and 7 show transition of link utilization for background traffic (1200 sessions at first generated: red line) and total 2400 sessions (blue line). As shown in Fig. 6, for background traffic in pattern a, SAR can schedule latter generated 1200 sessions so as to make link utilization smoothly flattened. In SAR-edge, high link utilization time interval generated by background traffic for each link is still high link utilization time interval after latter 1200 sessions are accommodated (see Fig. 6(b)). This is because in SAR-edge a router has no ability of time-shift of traffic peak and traffic peak generated at different timing at each link cannot be avoided only with time-dimensional scheduling at the sender side. FR starts its transmission as soon as possible, which leads to several time intervals with extremely high link utilization.

As shown in Fig. 7, SAR-edge and FR has poor performance from the viewpoint of smoothing link utilization. In pattern b, SAR also happen to have poor performance. This is because even with time-dimensional scheduling inside a network, high utilization time interval cannot be avoided. Even when a session can be scheduled to avoid peak traffic interval at a certain router, at any router beyond high utilization interval cannot be avoided. Fig. 8 simply explains this situation. As shown in Fig. 8(a), when peak traffic intervals line up in series, like pattern b, a path in time-

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space diagram cannot be found so as to avoid peak traffic intervals at all links. However, this happens only when peak time intervals line up clearly in series. When this sequence of peak time is broken even at one pair of links (see Fig. 8(b)), we can find a path avoiding peak link utilization. This means SAR can generally find a good path in time-space diagram. Even when there is a path(s) unfortunately having peak traffic interval in sequence, space dimensional routing might find another good path. In our future work, we will investigate and evaluate this space dimensional design of SAR.

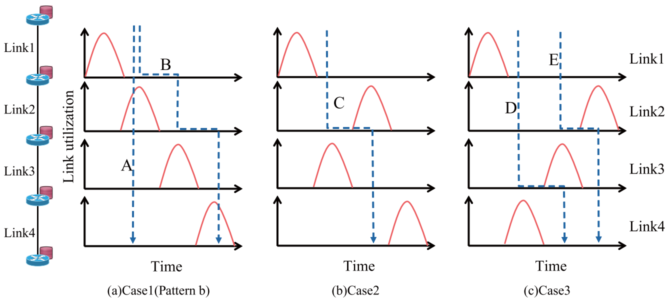

Figure 8. Path of session in case of every peak traffic interval

2) *Number of rejected sessions:* In this section, we evaluate SAR from viewpoint of number of rejected sessions. Further 1200 sessions are injected after accommodating 2400 sessions described in the previous section. These 1200 sessions are generated by the same distribution of session generation time and deadline as in the previous section. Table IV shows number of rejected sessions for session generation and deadline distribution of pattern *a* and *b*. In both cases, SAR has the lowest number of rejected sessions. So, SAR can design content file transmission timing so as to leave more room for upcoming sessions. It means that SAR can allow networks to accommodate traffic generated by users who want to watch video immediately.

IV. CONCLUSION AND FUTURE WORK

In this paper, we proposed a new traffic engineering technique for content distribution named SAR. When there is time difference between request generation time and content watching time, a user just cares about content is completely retrieved before her watching time and do not care about when it is retrieved. A router can schedule its transmission time in time-dimension when it has large storage. SAR makes use of this time-dimensional traffic control of scheduling of content file transmission time at each router in addition to the conventional space-dimension traffic control, i.e., routing. Numerical examples with binary integer programming formulation of SAR show that SAR can accommodate traffic so as to smooth link utilization at all links on the path. Our numerical example shows that there is limited condition where SAR cannot avoid high utilization interval. This limited condition of high link utilization interval set up in sequence along the path hardly happens, which means SAR generally works well. Even though this situation happens in a certain path, spatial routing can find another good path. Our next step is design of this spatial dimension routing of SAR. It is expected that the combination of spatial dimension routing and time dimension scheduling has more effect. Moreover, our future works are congestion avoidance on the storages and multicast using storages.

TABLE IV
NUMBER OF REJECTED SESSIONS

	pattern *a*	pattern *b*
SAR	4	224
SAR-edge	255	243
FR	657	669

ACKNOWLEDGMENT

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