Dynamic Bandwidth Allocation for a Space Relay Communications Network

Hui Zeng, Michael Hadjitheodosiou, and John Baras

Abstract—**We address issues related to efficiency, fairness, end-to-end delay minimization and Quality-of-Service framework in order to enable a flexible access and dynamic mission operation capability in the next generation NASA space-to-ground communication infrastructure. To provide optimal or near-optimal efficient utilization and fair allocation of bandwidth of the downlink channel while guaranteeing specific service requirements for different service classes, we propose two-level (long-term static and short-term dynamic) sharing of a slotted high data rate satellite communication link. The long-term optimal bandwidth allocation is implemented to provide per-stream/per-user service guarantee and give the inputs to the next level short-term dynamic bandwidth allocation. In our time-varying short-term bandwidth allocation with threshold regulation, a small portion of bandwidth is still assigned to all active spacecraft in advance but most bandwidth is dynamically allocated by the requests from them per frame by solving an optimal timeslot scheduling problem.**

I. Introduction

T he problem of Dynamic Bandwidth Allocation in a network that includes satellite links is very critical in both optimizing the expensive resource allocation and in guaranteed a particular Quality of Service to a variety of competing users [1]. The problem has been extensively studied for a variety of commercial satellite systems offering service to large numbers of users. In this paper however we focus on the allocation of bandwidth in a space relay network that supports several scientific spacecraft with a number of different streams on-board sharing a broadband satellite channel to send traffic to the ground. Our system model includes a number of mobile spacecraft (MS) in Lower Earth Orbit (LEO), a Geo-synchronous (GEO) relay satellite, and the ground network consisting of several ground stations (GS). The downlink channel of the relay satellite is shared by these spacecraft, which we model as streams with different priority levels going through a common queue and a router. The data will be delivered to the ground station through this relay.

To provide dynamic access with fairness and efficiency, a suitable hybrid-mode Time Division Multiple Access (TDMA) protocol along with frame-wise packet scheduling for bursty data flows was proposed for this network in [1]. It is shown that a carefully designed time-varying bandwidth allocation based on the instant or statistical traffic from all users/flows performs better in terms of throughput and end-to-end delay. However, only short-term (time varying) bandwidth allocation may cause instability and will have difficulties in providing Quality-of-Service (QoS) guarantees and managing the long-term (average) behavior of all the users/flows. Hence, we propose a two-level bandwidth allocation in our implemented TDMA scheme.

For a well-coupled framework with per user/flow average bandwidth management, we derive our long-term bandwidth allocation problem from the model discussed by Kelly in [2], and draw some ideas from work in [3, 4, 5]. In addition, for instantaneous bandwidth management, we incorporate ideas from some recent work [6, 7, 8] to formulate the short-term timeslot assignment problem and find the solution for optimal timeslot scheduling.

By using simulation, the performance of a suitable MAC protocol with two-level bandwidth allocation is analyzed and demonstrated to be better than that of the existing static fixed-assignment scheme in terms of End-To-End delay and successful throughput. We also study the fairness among all the users under a special scenario and find that the pseudo-proportional fairness is achieved for our hybrid protocol.

II. Two-level Bandwidth Allocation

A reservation protocol, which partitions the multi-access channel into reservation and data sub-channels in time division, as a variation of [9], is used here.

Every traffic source will be provided with a guaranteed QoS in terms of its triple request: LR (Lower Resource), TR (Targeted Resource) and UR (Upper Resource). Intuitively, the LRs and URs are the minimum and maximum bandwidth assignments to fulfill the data delivery according to the different requirements. And the TRs are the expected bandwidths to better satisfy the QoS requirements of the connections based on the traffic behavior.

Reservation mini-slots are used for access requests from new users. In the demands, every traffic source will provide

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its triple request: LR, RR and UR, and its priority level and weight when trying to get access to the channel. For certain types of traffic sources, three parameters might be redundant and therefore could be combined. This framework is similar to the studies presented by Hung [3] and the BoD protocol [4], but has a different parameter model.

As shown in the Fig. 1, the two-level bandwidth allocation is performed by the scheduler at the ground station at the Network Control Center (NCC). To access the channel, a new user first sends a request to the scheduler. After performing the admission control algorithm, the scheduler will broadcast its decision to the users. If the user is accepted, a static initial bandwidth allocation is made. Then the initial allocations will be sent to the short-term bandwidth allocator as control parameters for the next-level scheduling. Under some conditions, the long-term bandwidth allocation might be performed and updated to the next level too. In the short-term scheduler, according to the continuous bandwidth requests from users, the time-varying bandwidth allocation will be obtained and broadcasted. This is another reason why we use the triple request model, which gives us more control for the bandwidth management.
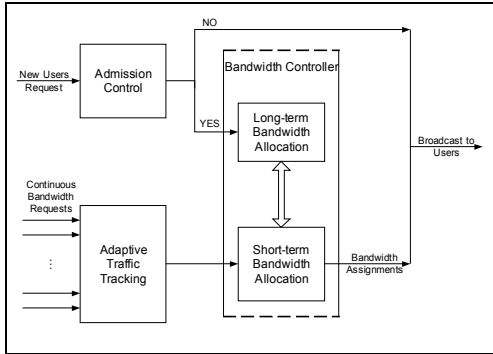

Fig. 1. Two-level Bandwidth Allocation at the Ground Station

III. LONG-TERM BANDWIDTH ALLOCATION

For access request from new user, the central scheduler performs the admission control algorithm to ensure the sum of the contracted bandwidths (rates) of all the users is less than or equal to the targeted bandwidth of the broadband channel. The user is allocated its PR as a sum of LR and a best-effort share from the available bandwidth, according to fairness and efficiency by solving an optimization problem. Here, long-term is referring to a relatively long time range compared with the short-term bandwidth allocation, which is performed per frame or in multi-frame basis.

Our long-term optimization problem is derived from the model in [2], so we will first briefly introduce the original framework in the following subsection, and then propose our formulation and solution thereafter.

A. Original Model(Ref [2])

Consider a network with a set L of resources or links and a set I of users. Let B_l denote the finite capacity of link $l \in L$. Each user has a route r, which is a non-empty subset of L. Define a 0-1 matrix A, where $A_{l,r} = 1$ if $l \in r$, and $A_{l,r} = 0$ otherwise. Suppose that if a rate (bandwidth) x_i is allocated to the user then $U_i(x_i)$ represents its utility. Here, the utility $U_i(x_i)$ is an increasing, strictly concave and continuously differentiable function of x_i over the range $x_i \geq 0$ (i.e., a elastic traffic). Also, utilities are additive so that the aggregate utility of rate allocation $x = (x_i, i \in I)$ is $\sum_{i \in I} U_i(x_i)$. Let $B = (B_l, l \in L)$ and $U = (U_i(\cdot), i \in I)$ and the rate-control optimization problem is formulated as following:

SYSTEM(U, A, B):

$$\max \ \sum_{i \in I} U_i(x_i) \tag{1}$$
$$subj. \ to \ Ax \ \leq \ B, x \ \geq \ 0.$$

From the convexity of the feasible region for x and the strict concavity of the logarithm function, it follows that the solution of (1) is unique and proportionally fair. We are interested in the proportional fairness or its variations because of its simpleness and popularity, although there are also other fairness criteria.

B. Utility Functions Discussion

Denote c = LR, b = UR, a = TR. To incorporate the LR (or c), we modify the utility function to $\log(x-c)$. To incorporate TR (or a), we want the optimal solution associated with the modified utility function has the following property: below its TR, the traffic source is very likely to get more bandwidth assignment if the price is payable; while some way beyond the TR, more bandwidth assignment is not that in need any more considering the price. In other words, the TR is a measure to describe the start point of the turning zone for the tradeoff between the resource and the price. Considering simple variations of logarithm functions, we list some candidates in Table I, where k, $k > 0$, is the desired attenuation parameter for the designated source.

TABLE I
COMPARISON OF UTILITY FUNCTIONS

$U(x)$	Region
$\log(x-c) - (x-a)/k$	$k \geq b - c$
$\log(x-c) - (x-a)^2/k$	$k \geq 2(b-a)(b-c)$
$\log(x-c) - \|x-a\|/k$	$k \geq b - c$

Recall that the utility function $U(x)$ is an increasing, strictly concave and continuously differentiable function of x over the range $x \in (c, b]$ for the elastic traffic. For strict concavity, the second derivative of $U(x)$ need to be negative, which is clearly correct except one point ($x = a$) for the 3rd

candidate utility function. To be increasing, the first derivative of $U(x)$ is nonnegative over the range $x \in (c, b]$, which leads to the regions specified in Table I respectively.

For detailed comparison with the above utility functions, we draw all of them and the truncated logarithm function in Fig. 2, with $c = 1$, $b = 8$, $a = 6$. As shown in Fig. 2, before the point $x = a$, the 2nd line is the most steep one among all the utility functions; while after the point $x = a$, it is the most flat one except the 3rd one. However, the 3rd line is the least steep one before the point $x = a$. Therefore we take the 2nd one, which is associated with the utility function

$$\log[(x-c) \cdot \exp(-(x-a)/k)] = \log(x-c) - (x-a)/k .$$

Also note that after the point $x = a$, the 2nd line and the 4th line coincide with each other.
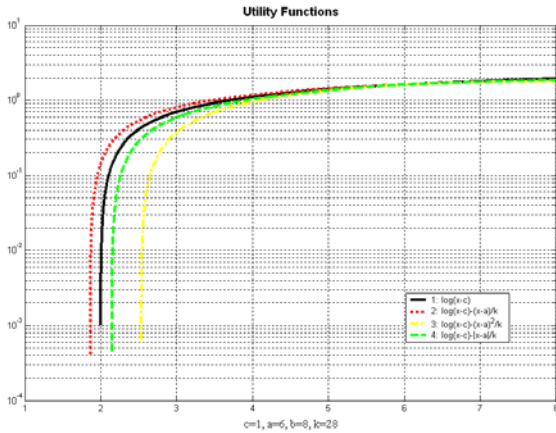

Fig. 2. Comparison of the Utility Functions

Note: semi-logarithmic scales. 1st: log(x-c), 2nd: log(x-c)-(x-a)/k, 3rd: log(x-c)-(x-a)²/k, 4th: log(x-c)-|x-a|/k.

C. Problem Formulation

Assume that the available bandwidth for each node is greater than the sum of the LRs in the same node. If for one specific node this assumption does not hold, the long-term bandwidth allocation problem is trivial. The feasible rate vector space X is defined as:

$$X = \left\{ x : x \in R^N, x > LR, x \leq UR \text{ and } Ax \leq B \right\},$$

and has at least one nonempty interior point. $LR = [LR_1, LR_2, ..., LR_N]^T$ is the vector of lower resource requests of N users, $UR = [UR_1, UR_2, ..., UR_N]$ is the vector of upper resource requests of N users. Recall that for simplicity we will use c, a, b to denote LR, TR, UR in the equations respectively.

Now our centralized bandwidth allocation problem is:

$$\max \sum_{i=1}^{N} [m_i \cdot \log(x_i - c_i) - \frac{x_i - a_i}{k_i}]$$

$$\text{subj. to: } x_i \geq c_i, x_i \leq b_i \quad (2)$$
$$Ax \leq B$$
$$i = 1, 2, ..., N$$

with assumption: $Ax_c < B$, where $x_c = [c_1, c_2, ..., c_N]^T$. Here, m_i is the weight for the source i, while x_i, c_i, a_i, b_i, k_i are defined for the source i.

D. Problem Solution

In (2) with linear constraints and our assumptions, the first-order Kuhn-Tucker conditions are the sufficient and necessary conditions for optimality. [10]

Now we consider the Lagrangian form:

$$L(x, \lambda, \beta, \mu) = \sum_{i=1}^{N} [m_i \cdot \log(x_i - c_i) - (x_i - a_i)/k_i]$$

$$- \sum_{i=1}^{N} \lambda_i(c_i - x_i) - \sum_{i=1}^{N} \beta_i(x_i - b_i) - \sum_{l=1}^{L} \mu_l[(Ax)_l - B_l],$$

$$x_i \geq 0, \lambda_i \geq 0, \beta_i \geq 0, \mu_i \geq 0, i = 1, ..., N,$$

where λ_i, μ_i, β_i, $i = 1, ..., N$, are slack variables associated with LRs, URs and capacity constraints.

And by considering the sufficient and necessary conditions, we obtain the unique solution as follows:

$$\forall i = 1, ..., N, \quad \forall l = 1, ..., L,$$

$$x_i = c_i + \min \left[(b_i - c_i), \frac{m_i}{\frac{1}{k_i} + \sum_{l=1}^{L} \mu_l A_{l,i}} \right] \quad (3)$$

$$Ax \leq B, (Ax - B)_l \cdot \mu_l = 0, \mu_l \geq 0.$$

According to the discussion previously, the optimal point x has the property that for any perturbation, when $m_i = 1$,

$$\sum_{i \in I} \delta x_i / (x_i - c_i) \leq \sum_{i \in I} \delta x_i / k_i ,$$

which is similar as the proportional fairness. Then nearby the optimum point, the aggregation of the relative changes of all the sources will be upper-bounded, although not zero. We call it "pseudo-proportional fairness". When $(k_i, i \in I)$ are large enough, the upper bound will be small, even close to zero. We will see this property is well-coupled with the short-term time-varying bandwidth allocation in section V.

We have several other useful remarks for the obtained optimal solution:

1. The Lagrange multiplier μ_l is the implied cost of unit user through link l, or the shadow price of additional unit capacity for link l.

2. For one specific user, the assigned bandwidth is explicitly dependent of the link costs and its own parameters, while implicitly dependent of the users in other nodes.

3. m_i is the weight for the user i. The user with higher m_i has better opportunity to get more bandwidth than the user with lower one in the same node.

4. k_i is the desired attenuation parameter for the source i. Assume that k is proportional to *(a-c)* and *(b-c)*, while inversely proportional to *(b-a)*, then we have that

$$k \propto \frac{a-c}{b-a}(b-c) .$$ Again, the user with higher k_i has

better opportunity to get more bandwidth than the user with lower one.

From the discussions above, we see that our framework has one more parameter (TR) which models the turning point of user's request. And by increasing the utility function before TR while decreasing it after TR, we make the bandwidth allocation more reasonably among all the users while maintaining similar property as proportional fairness. At the same time, the importance of TR is modeled by k_i. With higher k_i, the effect of TR on our framework is smaller.

Now consider the asymptotic property of k_i. Recall that $k_i \geq b_i - c_i, \forall i = 1,...,N$. As all k_i go to ∞, it follows that our objective function

$$\max \sum_{i=1}^{N} [m_i \cdot \log(x_i - c_i) - (x_i - a_i)/k_i]$$

$$\rightarrow \max \sum_{i=1}^{N} [m_i \cdot \log(x_i - c_i)],$$

which is exactly the one with proportional fairness discussed in [2, 5] when $m_i = 1$. As a result, our optimal solution here is exactly the one in [5] as all k_i go to ∞. Also, with k_i increasing, the attenuation for the source i is decreased, and then the possibility for the source i to get more bandwidth after certain point is increased. This just shows the relation between our model with the model associated with proportional fairness.

IV. DYNAMIC BANDWIDTH ALLOCATION

In this section we formulate the general time-varying dynamic bandwidth allocation problem for slotted TDMA protocol in space communications network based on the parameters determined by the long-term bandwidth allocation, and then find its solution.

Let M denote the complete set of all MS, and M_a denote the set of active MS generating traffic. The central ground station performs the burst-level scheduling, i.e., the scheduling only occurs once during each frame and allocates timeslots to a stream within a frame in a contiguous fashion. The scheduler generates a bandwidth allocation table (BAT) and sends it back to all the MS in the set M_a. Then each active MS knows its assigned timeslots after reading the BAT.

A. Problem Definition

Let N denote the number of the total available data slots. We consider the penalty weights v_{kl}, $k \in M_a$, $l \in C$ for the service class l of the MS k to reflect the QoS and different requirements. For different slots assignment, the aggregated penalty can be calculated with the definition of these penalty weights and the utility function. Our objective for the optimal scheduling is to find the solution to minimize the total penalty.

Every time before making the BAT, the scheduler collects the updated information including the number of MS and active MS, the bandwidth demands (D) of active MS and the penalty weights. To present the different types of traffic, let C denote the set of service classes. Thus, D is a two dimension matrix $\{D_{kl}\}$, $k \in M_a$, $l \in C$. D could be directly given by the MS or computed by the collected information from the MS. The latter is more practical while more complicate since an estimation step is must. The PR, i.e., $(x_i, i = 1, ..., N)$, are used as parameters for calculation. We use a matrix $s = \{s_{kl}\}$ to denote the amount of assigned data slots for service class $l \in C$ of the MS $k \in M_a$.

B. Problem Formulation

Now we can formulate our problem as below:

$$\text{Minimize} \quad \sum_{k \in M_a} \sum_{l \in C} v_{kl} (D_{kl} - s_{kl})^+ \tag{4}$$

subject to:

$$s_{kl} \leq \min(U_{kl}, D_{kl}), \qquad k \in M_a, l \in C$$
$$s_{kl} \geq L_{kl}, \qquad k \in M_a, l \in C$$
$$\sum_{k \in M_a} \sum_{l \in C} s_{kl} \leq N,$$
$$\forall s_{kl} \in \{0, 1, 2, ..., N\}$$

If a MS requests more timeslots than the available data slots which can be assigned to it, only a portion of its request slots will be actually admitted and the residual packets must wait for the next scheduling. Let U_{kl} and L_{kl} denote the upper bound and lower bound of capacity for the service class $l \in C$ of MS $k \in M_a$, respectively. The LR and UR from the user via long-term bandwidth could be used directly here. Some mappings from LR and UR are also possible. The PR, i.e., $(x_i, i = 1, ..., N)$, are used as parameters for bounded assignment. The upper bound of waiting time (delay) for the service class $l \in C$ of MS $k \in M_a$ is set and used in the decision of penalty weights to guarantee the maximum delay if necessary.

C. Problem Solution

The solution can be obtained by these steps:

1. **Sorting:** Sort the penalty matrix $\{v_{kl}\}$ and re-list them in a vector V in the descending order.
2. **Lower Bound assignment:** Determine the number of data slots for the active MS to satisfy the lower bound requirements.
3. **Additional Amount assignment:** Assign the available slots to the active MS according to the order in the vector V until the demand or upper bound is fulfilled.
4. **Final assignment:** Allocate timeslots to each user within a frame in a contiguous fashion.
5. **Create the BAT**.

Our problem formulation has two assumptions: 1). The demands D_{kl}, upper bounds U_{kl} and lower bounds L_{kl} are known or could be determined by the scheduler. 2). The penalty weights v_{kl} are distinct. Another concern is that our problem should consider the multi-frame condition in the space communications network with long propagation

delay.

We make some improvements for these concerns. Usually the U_{kl} and L_{kl} can be assigned according to the service requirements of the streams and the practical condition of the whole channel, and can be viewed as two adjustable parameters. Let t_0 and t denote the time the request was created in the MS and processed in the scheduler respectively. Between t_0 and t, the total assigned timeslots for the service class l of the MS k is called "credit" and denoted by $Ct_{kl}(t_0, t)$. Similarly, the total incoming packets between t_0 and t plus the number of packets in queue at time t_0 for the service class l of the MS k is called "debit" and denoted by $Dt_{kl}(t_0, t)$. Then, the "balance", which is $[Dt_{kl}(t_0, t) - Ct_{kl}(t_0, t)]^+$, is a very practical determination of the demand D_{kl}. The cumulative bandwidth assignment for one user is upper bounded by its (PR × frames + U) and lower bounded by its (PR × frames − L). Notice that it considers the multi-frame condition for the long propagation delay. The penalty weights v_{kl} are assigned discrete values based on the relations between the "balance" and some prescribed thresholds. When v_{kl} of some streams are same, the calculated demands D_{kl} are used to determine their order in the first step.

V. Configuration and Simulation Results

A. Network Configuration

We use OPNET to model the MAC protocol and network scenario. For simplification, we use only one relay satellite, and consider four LEOs in its coverage zone with the altitude range of 701-716 km. The RTD is more than 0.6 seconds in this case. We set $M \cdot T_f$ = 0.68 seconds and the number of data slots per frame as 64. The total data rate of the link is 200Mbps and we consider a sub-channel with 2Mbps capacity and accordingly 1/100 of data rate of all spacecraft. Hence, by combining these parameters and the length of source packet (512 bytes), we set $M = 5$, and get T_f = 0.1372 sec. The downlink channel is assumed to be error-free.

We are particularly interested in the total throughput, which in a sense provides an indicator of the level of bandwidth efficiency; and ETE delay, which is the time interval between its generation on-board spacecraft and its arrival at the ground station.

The network traffic is diverse, i.e., the traffic loads are unevenly distributed among the spacecraft. Also, the source traffic data rate in a specific spacecraft varies considerably. Those properties match the unpredictable and dynamic traffic pattern in this environment. Also, specific spacecraft could probably be inactive for a period of time, and an adaptive protocol would be capable to accommodate that.

B. Simulation Results

Our simulation is run for several minutes to reach steady-state. We try to adjust the simulation time to take within the limit of having the spacecraft inside the common coverage zone under one TDRS relay satellite is limited. Note that the spacecraft are orbiting with high velocity (typically their orbit periods are around 95 minutes).

We first present the performance of the hybrid protocol under unevenly distributed traffic load. Then the ETE-delay and successful throughput performances of a conventional (static) TDMA solution will be compared with this protocol. As shown in Fig. 3, the ETE delay is ranging from 0.26 seconds to less than 0.5 seconds under different traffic loads with different numbers of active spacecraft. Considering the large propagation delay and the large variation of it because of the spacecraft mobility, this is very good. Basically any dynamic schemes without the similar enhancement or modification as ours could not work well in our scenario or even turn instable. From Fig. 3, we can obviously see that, the less active spacecraft we have, the better performance the protocol will have.
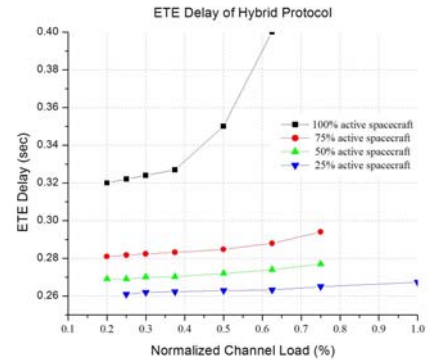

Fig. 3. ETE Delay of Hybrid Protocol

Now we fix the ratio of expectations of traffic loads of four users (spacecraft) as 3:2:2:1, and study the performance of our hybrid protocol in terms of ETE delay, successful throughput and the fairness under this special scenario. As shown in Fig. 4, the hybrid protocol outperforms the fixed TDMA in terms of ETE delay and successful throughput. This is because the hybrid protocol can utilize the data slots once belonging to the inactive spacecraft or spacecraft at low data rate in a short range, while in the fixed TDMA, these data slots are just wasted. Another reason is that in the hybrid protocol, the data slots are dynamically assigned based on the behavior of their traffic, and therefore achieve the better bandwidth utilization. The more bursty and unpredictable the traffic sources are, the more the hybrid protocol will outperform a fixed TDMA solution.
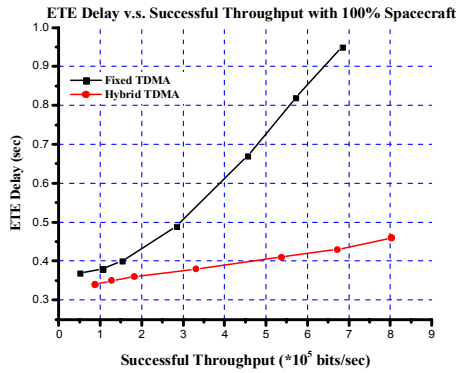
Fig. 4. ETE Delay vs. Throughput

To study the (long-term) fairness among all the users, the successful average throughputs of the total channel and every individual user are shown in Fig. 5. As we can see, although obviously the proportional fairness is not achieved, the pseudo-proportional fairness is obtained in some sense. In other words, the average share of the channel for every user is close to its proportional portion according to the expectations of traffic loads of four users, i.e., 3/8, 2/8, 2/8 and 1/8 respectively. Since we use the order of the users to break the tie sometimes in the dynamic bandwidth allocation, the average throughput of the user 2 is always a little higher than that of the user 3 despite that they have same traffic loads.
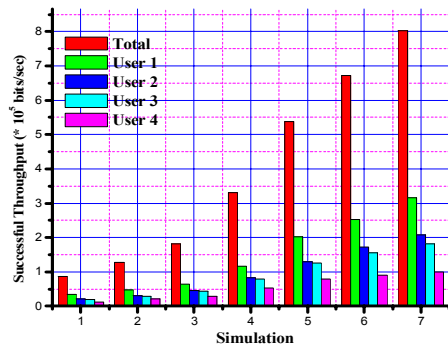

Fig. 5. Fairness among Users

VI. SUMMARY & FURTHER WORK

To provide optimal or near-optimal efficient utilization and fair allocation of bandwidth of the downlink channel while guaranteeing specific QoS requirements for different service classes, we propose two-level bandwidth allocation for a slotted TDMA high data rate satellite communication link. The long-term bandwidth allocation is implemented to provide per-flow/per-user QoS guarantee and shape the average behavior. In our time-varying short-term bandwidth allocation with threshold regulation, a dynamic allocation is performed by solving an optimal timeslot scheduling problem according to the requests and other parameters. By using simulation, the performance of a suitable MAC protocol with two-level bandwidth allocation is analyzed and compared with that of the existing static fixed-assignment scheme in terms of ETE delay and successful throughput. We also study the fairness among all the users under a special scenario and find that the pseudo-proportional fairness is achieved for our hybrid protocol.

In a space communications network, the propagation delays are not only significant, but also variable among users due to their different geographical locations. Moreover, when moving objects are used as source nodes, the propagation delays are time-varying. Besides, when the queuing delays in the source and intermediate nodes are considered, the communication delays are also time-varying. So, we need to formulate rate-control system models with heterogeneously time-varying large propagation delays, and then study its stability and other behavior. We are currently focusing on analyzing the effect of the time-varying delay and the time-varying service rate by defining delayed proportional relation between service rate and queue size and then analyzing the multi-flow system model.

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