Multi-Pool Based Resource Allocation Scheme in Broadband SATCOM System

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***Abstract*—A Multi-Satellite Broadband Network (MSBN) appears to be a promising network for providing efficient and seamless multimedia services. To maximize the resource utility and optimize the Quality of Service (QoS) in MSBN, reasonable bandwidth allocation method is, indeed, important. State-of-the-art bandwidth algorithms, which are mostly based on the allocation of a single satellite-ground link, ignore limited traffic capacities in other links, such as inter-satellite links. In this paper, a Multi-Pool based Bandwidth Allocation (MPBA) scheme is proposed to solve this problem. Firstly, a typical multi-pool framework is built to manage bandwidth resources of all communication links instead of the traditional single satellite-ground link, and the corresponding resource allocation process is analyzed. Secondly, inspired by the non-cooperative game theory, the MPBA algorithm with a low computation complexity is designed to ensure different QoS demands of multimedia services. Extensive experiments are carried out, and results obtained demonstrate that our multi-pool framework can achieve improvement on the end-to-end delay and the network resource utility over existing bandwidth allocation methods in MSBN.**

***Keywords*–Resource Allocation; Satellite Communication; Multimedia services; Quality of Service.**

I. INTRODUCTION

Future broadband satellite communication (SATCOM) systems will be composed of multiple satellites and orbits to provide efficient multimedia services [1] [2], which is called multi-satellite broadband network. Notwithstanding the benefits stemming from this design approach, owing to the diversity of communication links, the system must be capable of managing all of the bandwidth resources in every communication link flexibly, with satellite-ground links and inter-satellite links included. There are three key points that must be considered in the bandwidth allocation scheme of MSBN:

- Guarantee different QoS demands for multimedia services.
- Maximize the network resource utility.
- Balance traffic loads of different links.

State-of-the-art broadband SATCOM system based bandwidth allocation algorithms have made great contributions on the first two points. A game-theoretic framework based on Nash bargaining solution from cooperative game theory for the bandwidth allocation of elastic services in high-speed networks is proposed in [3], which is the first to focus on different QoS requirements of multimedia services in bandwidth allocation. It provides the rate setting of users that are Pareto optimal from the point of view of the whole system. Based on the water-filling algorithm, a cross-layer framework for optimizing the dynamic bandwidth allocation of Digital Video Broadcasting - Return Channel via Satellite (DVB-RCS) system is proposed in [4]–[8], which takes the Media Access Control (MAC) layer into consideration and provides QoS requirement for multimedia services in dynamic satellite channels. Rain-fade attenuation is taken into consideration on the bandwidth allocation scheme in [9], which makes contribution on the real-time slot assignment. The resource allocation is modeled as a non-cooperative game in [10], and a fair equilibrium point is converged to improve the fairness.

However, [3]–[10] are based on the resource allocation of a single satellite-ground link, which means that they ignore the limited traffic capacity of other links in MSBN, such as inter-satellite links. Traditional bandwidth allocation schemes [3]–[10], without taken the third point into consideration, are actually local optimization methods, which could not achieve system optimization in MSBN.

In a typical scenario of MSBN, as is shown in Figure 1, for satellite node S_i with B spot beams, the resource pools can be divided into three types: $S_i^k (k = 1, ..., B)$, $S_i \to S_j$, $S_j \to S_i$. S_i^k refers to the resource pool of k-th satellite-ground link in satellite S_i, $S_i \to S_j$ is the resource pool of inter-satellite link from satellite S_i to S_j, and $S_j \to S_i$ is from S_j to S_i.

It can be observed from Figure 1, that $user_1$, accessing B_1-th spot beam of satellite S_1, initiates a communication request with $user_2$, with $user_2$ accessing B_2-th spot beam of S_4. Supposing the optimal route path of the communication from $user_1$ to $user_2$ is $S_1 \to S_2 \to S_4$, then bandwidth resources of resource pools $S_1^{B_1}$, $S_1 \to S_2$,$S_2 \to S_4$, and $S_4^{B_2}$ will be occupied by this communication.

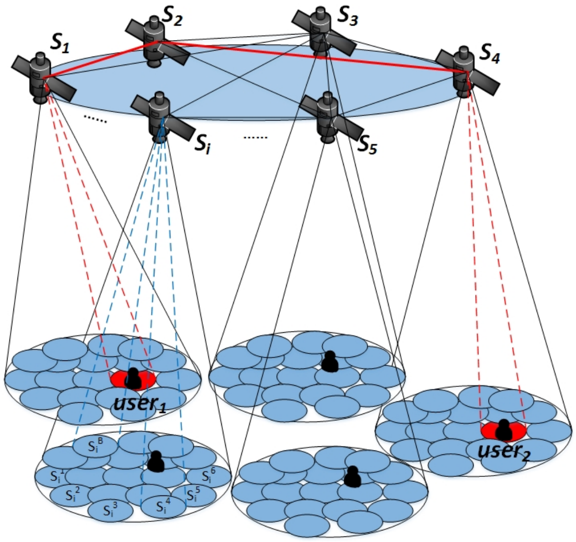

Figure 1. The resource framework in MSBN

Traditional researches [3]–[10] just take the bandwidth capacity of access link $S_1^{B_1}$ into consideration, as much service as $S_1^{B_1}$ can afford will be admitted to achieve higher local resource utilization. However, with the lack of considering the limited capacity of inter-satellite links, there will be plenty of packets congestions in inter-satellite links, which will deteriorate the end-to-end delay and will increase the packet loss, especially when the system throughput rate is high. And lossless protocols, such as TCP, require retransmission of lost packets, which substantially increases transmission time and deteriorates congestion in inter-satellite links.

In this paper, we propose a multi-pool based bandwidth allocation scheme, which manages all links dynamically and minimizes network congestions in MSBN, to make up for the drawbacks of traditional methods above. By taking diversity QoS demands of multimedia services into account, our method can keep the resource utilization to maximum, while satisfying QoS demands of different multimedia services at the same time. By adopting the gradient descent and the non-cooperative game theories, a priority based bandwidth allocation algorithm is proposed to achieve network utility maximum (NUM) in our MPBA method, which features a low computational complexity and guarantees different QoS demands of multimedia services in MSBN.

The rest of this paper is organized as follows: In Section II, the multi-pool bandwidth optimization framework is constructed and the corresponding optimization problem is presented, which means to afford assurance of different QoS demands for multimedia services. In Section III, a non-cooperative theory based algorithm is proposed to solve the optimization problem and the complexity of this algorithm is analyzed. In Section IV, a simulation scenario is built based on OPNET, and comparison results of the MPBA and the traditional algorithm on the network end-to-end delay and the system resource utility are analyzed. The conclusion of this paper is given in Section V.

II. PROPOSED SYSTEM MODEL

A. A Multi-pool based Resource Allocation Framework

As is shown in Figure 1, the traffic would occupy bandwidth resource of links within its route path. As a result, the traffic carrying capability of all these related links, not just access link, should be taken into consideration in the decision of whether a traffic could be accepted. Giving this situation, a MPBA framework is proposed in this paper. The process of the MPBA framework can be divided into four steps:

1. A bandwidth request is initiated by $user_i$ to the system Radio Resource Manager (RRM), with the destination node, the user type, the service type, the minimum bandwidth requirement $a_i$bps, and the current bandwidth requirement $b_i$bps included.

2. The RRM asks for the optimal route path information of $user_i$ from the network route manager.

3. The RRM obtains remaining bandwidth informations of all relevant satellite-ground and inter-satellite links within the optimal route path of $user_i$.

4. The RRM checks if all related links can meet the bandwidth demand of $user_i$. The bandwidth request of $user_i$ will be successful only when all links can meet the requirement. Otherwise, a bandwidth allocation failure signaling would be sent to $user_i$.

Different from traditional model [3]–[10], the traffic capacities of every link in system, rather than only the access link, are considered in the MPBA scheme, which is the key that global optimism could be achieved in MSBN.

There are different types of multimedia services in MSBN. The key of bandwidth allocation is to meet different QoS demands of multimedia services while maximizing the system resource utility. The MSBN based optimization problem is analyzed below.

B. Problem Formulation

Define a link vector $\mathbf{L} = (l_1, l_2, ..., l_M)$, where l_i is the i-th link in MSBN and M is the number of links in MSBN. Let the link resource vector $\mathbf{C} = (C_1, C_2, ..., C_M)$ be the current remaining bandwidth of links in $\mathbf{L}$, set $Q = \{user_1, user_2, ..., user_K\}$ consists of users to be allocated bandwidth resources. For multimedia $user_i (i = 1, 2, ..., K)$, let a_i be the minimum bandwidth demand and b_i be the current requested bandwidth.

The utility function is a tool of measuring the cost and the benefit in the bandwidth allocation. The user utility function $u_i(x_i)$ of $user_i$ is a classical model [11] [12], which meets

$$u_i(x_i) = P_i * \ln(x_i + 1) \tag{1}$$

where x_i denotes the allocated bandwidth resource, P_i is the traffic priority, the system utility function $U = \sum_{i=1}^{K} u(x_i)$ is the sum of all user utility values.

Then, we model the optimization problem of the bandwidth allocation in MSBN as follows:

$$\mathbf{P}: \quad \max \sum_{i=1}^{K} u_i(x_i) \tag{2}$$

$$\text{s.t.} \quad \mathbf{Ax} \leq \mathbf{C} \tag{3}$$

$$(\mathbf{a} \leq \mathbf{x} \leq \mathbf{b}) \cup ((\mathbf{x} = \mathbf{0}) \cap (\mathbf{x} \in \mathbf{N})) \tag{4}$$

Equation (4) constraints that the allocated resource for the $user_i (user_i \in Q)$ should meet the minimum bandwidth request $a_i (a_i \in \mathbf{a})$ and less than the maximum demand $b_i (b_i \in \mathbf{b})$, and, at the same time, the allocated resource $x_i (x_i \in \mathbf{x})$ should be an integer. if it cannot meet the minimum demand, the system would not allocate resources for the user, which means that $x_i = 0$. Matrix $\mathbf{A}$ represents the connection between $l_j (l_j \in \mathbf{L})$ and $user_i (user_i \in Q)$, which meets

$$\mathbf{A} = \begin{cases} \mathrm{A}_{ji} = 1, & \text{the route path of } user_i \text{ through } l_j \\ \mathrm{A}_{ji} = 0, & \text{otherwise} \end{cases} \tag{5}$$

where $\mathbf{A} \in \Re^{M \times K}$ and the route path of $user_i$ is computed by Dijkstra algorithm [13].

As is shown in (3), the link bandwidth constraint condition is multi-dimensional, which is different from the one-dimensional constraint condition in the traditional model [3]–[10]. Notwithstanding the benefits stemming from this design, owing to the multi-dimensional of link capacity constraint in (3) and discontinuous constraint in (4), this optimization problem can not be solved with the traditional method. Inspired by non-cooperative game theory, a multi-pool resource allocation algorithm is proposed to solve this optimization problem.

III. THE MULTI-POOL RESOURCE ALLOCATION ALGORITHM

Considering that the constraints of the original optimization in (2) is complex, we separate the optimization into two subproblems to iteratively obtain the global optimization of the original problem.

A. Obtain Lagrange Approximate Solution

Given the optimization problem in (2) is a strictly increasing and convex function, if just the continuity constraint condition in (3) is considered, according to the Lagrangian duality theory [14] and the convex programming theory [15], this problem can be solved with Lagrangian multiplication. The Lagrange expression of optimization problem in (2) is

$$\mathcal{L}(\mathbf{x},\lambda) = \sum_{i=1}^{K} P_i \times \ln(x_i+1) - \lambda^{\mathrm{T}}(\mathbf{Ax}-\mathbf{C})$$
$$\text{s.t.} \qquad \lambda \geq \mathbf{0}, \lambda \in \Re^{M\times 1} \tag{6}$$

The derivative of (6) is as follows:

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}x_i} = \frac{P_i}{x_i+1} - \sum_{j=1}^{M} \lambda_j A_{ji} = 0 \quad (i=1,2,...,K) \tag{7}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\lambda} = \mathbf{Ax} - \mathbf{C} = \mathbf{0} \tag{8}$$

Then we have:

$$x_i = \frac{P_i}{\sum_{j=1}^{M} \lambda_j \mathrm{A}_{ji}} - 1 \qquad (i=1,2,...,K) \tag{9}$$

$$\sum_{i=1}^{K} \mathrm{A}_{ji} x_i = C_j \qquad (j=1,2,...,M) \tag{10}$$

Inspired by the gradient descent method [16], we set the iterative equation as follows:

$$x_i^{n+1} = \max(0, \min(\frac{P_i}{\sum_{j=1}^{M} \lambda_j^n \mathrm{A}_{ji}} - 1, \min(\mathrm{A}_{ji}C_j, C_j \in C)))$$
$$(i=1,2,...,K) \tag{11}$$

$$\lambda^{\mathbf{n+1}} = \max(\mathbf{0}, \lambda^{\mathbf{n}} - \mathbf{r^n}\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\lambda^{\mathbf{n}}}) \tag{12}$$

where $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\lambda^{\mathbf{n}}} = \mathbf{Ax^n} - \mathbf{1}$, and $\min(\mathrm{A}_{ji}C_j, C_j \in C)$ in (11) denotes the minimum remaining bandwidth resources in related links, which guarantees the convergence of the iteration. The initial step value of the iteration step is $\mathbf{r^0}$, $\mathbf{r^{n+1}} = \mathbf{r^n} * \mathbf{T}(\mathbf{n}=\mathbf{0},\mathbf{1},...)$, where $\mathbf{T}$ is the attenuation factor, which determines the iterative rate.

The initial iteration value $\begin{pmatrix} \mathbf{x^0} \\ \lambda^{\mathbf{0}} \end{pmatrix}$, which is the key of convergence rate, is analyzed in this paper. Let N_i be the number of links occupied by $user_i$, which obeys $N_i \sim U(1,M)$. According to the probability density function theory, the average number of links is $\frac{M+1}{2}$, thus we can set $x_i^0 = \frac{2*\sum_{j=1}^{M} C_j}{(M+1)K}(I=1,2,...,K)$. Since the traffic priority P_i can be normalized to $P_i \sim U(0,1)$, we get $\lambda_j^0 = \frac{K}{(M+1)K+2*\sum_{j=1}^{M} C_j)}(j=1,2,...,M)$ from (9).

Let the iterative error factor be $\Delta = \|\lambda^{i+1} - \lambda^i\|_2$ and the iterative precision be I_M, the iterative process ends until $\Delta \leq I_M$. After that, the Lagrangian approximation solution $\tilde{\mathbf{x}} = (\tilde{x}_1, \tilde{x}_2, ..., \tilde{x}_K)^{\mathrm{T}}$ is obtained, and according to the strong duality theory in the convex optimization, the approximate optimal solution is unique.

B. Remove Maximum and Minimum Bandwidth Constraint

Considering the discontinuous constraint condition in (4), a non-cooperative theory based method is used to achieve the global optimal solution in this paper.

Firstly, assume that the set of users who meet $x_i = 0$ is G_1, the set of game users is G_2, the set of users who game success is G_3, and initialize $G_1 = \emptyset$, $G_2 = Q$, $G_3 = \emptyset$.

Definition 1. (Remove Maximum Bandwidth Constraint)

Obtain the Lagrangian approximate solution of all users in G_2 is $\tilde{\mathbf{x}} = (\tilde{x}_1, \tilde{x}_2, ..., \tilde{x}_N)^{\mathrm{T}}$, for every $user_i(user_i \in G_2)$, if $\tilde{x}_i > b_i$, then remove $user_i$ from G_2 to G_3, and set the allocated bandwidth for $user_i$ be $x_i = b_i$, and update the remaining bandwidth of every resource pool $C_j(C_j \in \mathbf{C})$ be $C_j = (C_j - \mathrm{A}_{ij}b_i)$.

We define the process of removing all game success users from G_2 to G_3 above as a subroutine. Continue iteratively through this subroutine, until the Lagrangian approximate solution of every user in set G_2 meets $\tilde{x}_i \leq b_i(\tilde{x}_i \in \tilde{\mathbf{x}})$.

Definition 2. (Remove Minimum Bandwidth Constraint)

Execute the process of Remove Maximum Bandwidth Constraint in Definition 1, then obtain the Lagrangian approximate solution of all users in G_2 is $\tilde{\mathbf{x}} = (\tilde{x}_1, \tilde{x}_2, ..., \tilde{x}_N)^{\mathrm{T}}$. Define a set $G_4 = \emptyset$, for every $user_i(user_i \in G_2)$, if $\tilde{x}_i < a_i$, then copy $user_i$ from G_2 to G_4. Define the utility rate $R_i = \frac{u(a_i) - u(\tilde{x}_i)}{a_i - \tilde{x}_i}$, and the $user_m(user_m \in G_4)$ whose utility rate R_m is minimum is removed from G_2 to G_1, then set the allocated bandwidth for $user_m$ be $x_m = 0$.

We define the process of removing the user with minimum utility rate from G_2 to G_1 above as a subroutine. Continue iteratively through this subroutine, until the Lagrangian approximate solution of every user in set G_2 meets $\tilde{x}_i \geq a_i(\tilde{x}_i \in \tilde{\mathbf{x}})$.

Theorem 1. The process of Remove Maximum Bandwidth Constraint in Definition 1 is the optimal solution for users in G_3.

Proof. According to the reduction to absurdity, we take a hypothesis as follows:

After the process of Remove Maximum Bandwidth Constraint, there are $user_i \in G_3$ and $user_j \in G_2$, which meet

$$u_i(b_i - 1) + u_j(\tilde{x}_j + 1) > u_i(b_i) + u_j(\tilde{x}_j) \tag{13}$$

The hypothesis in (13) could be reduced to

$$\frac{u_i(b_i) - u_i(b_i-1)}{b_i - (b_i - 1)} < \frac{u_j(\tilde{x}_j+1) - u_j(\tilde{x}_j)}{(\tilde{x}_j + 1) - \tilde{x}_j} \tag{14}$$

Since the utility function $u_i(x_i) = P_i * ln(x_i+1)$ is logarithmic, its derivative function is strictly monotonically decreasing. According to the Lagrange Mean Value Theorem, $\exists\ b_i > \xi_i > (b_i - 1), (\tilde{x}_j + 1 > \xi_j > \tilde{x}_j)$, which meets:

$$u_i'(\xi_i) = \frac{u_i(b_i) - u_i(b_i-1)}{b_i - (b_i-1)} \tag{15}$$

$$u_j'(\xi_j) = \frac{u_j(\tilde{x}_j + 1) - u_j(\tilde{x}_j)}{(\tilde{x}_j + 1) - \tilde{x}_j} \tag{16}$$

From inequality (14), we get

$$u_i'(\xi_i) < u_j'(\xi_j) \tag{17}$$

However, with the process of Remove Maximum Bandwidth Constraint in Definition 1, the optimal solution obtained by the Lagrangian multiplication method in set G_2 meets

$$\frac{\mathbf{d}\mathcal{L}}{\mathbf{d}\tilde{x}_i} = u_i'(\tilde{x}_i) - \sum_{l=1}^{M} \lambda_l \mathrm{A}_{li} = 0 \tag{18}$$

We get

$$u_i'(x_i) = \sum_{l=1}^{M} \lambda_l \mathrm{A}_{li} = \sum_{l=1}^{M} \lambda_l \mathrm{A}_{lj} = u_j'(x_j) \tag{19}$$

Thus, due to the decreasing property of $u_i'(x)$ and $u_i'(x)$, then

$$u_i'(x_i) > u_i'(b_i) \geq u_i'(x_i) = u_j'(x_j) \geq u_j'(x_j) \tag{20}$$

Since the contradiction of (17) and (20), the hypothesis in (13) is false. Thus, we verify the validity of Theron 1.

Theorem 2. The process of Remove Minimum Bandwidth Constraint in Definition 2 is the optimal solution for users in G_1 and G_3.

Proof. Because the subroutine which finds the user with minimum utility rate R_i is a greedy algorithm [3], the optimal solution could be achieved for users in G_2 with the execution of subroutine.

We define the system utility of i-th subroutine in Definition 2 as U_{opt}^{i} and the iterative time as n.

When $n = 1$, the system utility U_{opt}^{1} could achieve maximum after the execution of the first subroutine. And we have $U_{opt}^{1} > U_{opt}^{0}$.

When $n = k$, the optimal solution could be achieved for users in G_3 with the process of Remove Maximum Bandwidth Constraint, and for users in G_2 with the process of finding the minimum utility rate R_i. Thus, the maximum value of the system utility U_{opt}^{k} could be achieved with the process of k-th subroutine, and we have $U_{opt}^{k} > U_{opt}^{k-1}$.

The iteration of this subroutine is completed until all users in G_2 satisfy $a_i \leq \tilde{x}_i \leq b_i$. The iterative time is denoted as N, and the system utility is U_{opt}^{N}, which meets

$$U_{opt}^{N} > U_{opt}^{N-1} > ... > U_{opt}^{k} > ...U_{opt}^{1} > U_{opt}^{0} \tag{21}$$

Since the iteration of the subroutine is completed, with the conclusion in (21), thus, we verify the validity of Theorem 2.

With the theoretical analysis above, the algorithm of solving the optimization problem in (2) could be expressed in Algorithm 1.

Algorithm 1 The Multi-Pool based Resource Allocation algorithm

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Input: The parameter of set $Q$ for users; the maximum iterative time $I$ in Definition 2.
Output: The allocated bandwidth $\mathbf{x}$ for users in set $Q$.
Set $G_1 = G_3 = \emptyset$, $G_2 = Q$;
$f_{min} = 0$;
for $i = 1 \to I$ do
    if $f_{min} = 0$ then
        Execute the process of Removing Maximum Bandwidth Constraint in Definition 1.
        Obtain the Lagrangian approximate solution in set $G_2$.
        Set $G_4 = \emptyset$, and copy all users who meet $\tilde{x}_i < a_i$ from $G_2$ to $G_4$.
        if $G_4 \neq \emptyset$ then
            Find the $user_m$ with the minimum value of the utility rate $R_m$ in $G_4$, and remove $user_m$ from $G_2$ to $G_1$, set the allocated bandwidth for $user_m$ be $x_m = 0$ .
        else
            $f_{min} = 1$;
        end if
    else
        break;
    end if
end for
Set the allocated bandwidth for users in $G_2$ as $x_i = \lfloor \tilde{x}_i \rfloor$, where $\lfloor \tilde{x}_i \rfloor$ is the rounded down value of $\tilde{x}_i$.
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C. Complexity Analysis

Let K be the maximum number of iterations in the gradient descent process, so the complexity in solving the Lagrangian multiplication is $O(K)$. The complexity of the process of Remove Maximum Bandwidth Constraint in Definition 1 is $O(KN_Q \log_2 N_Q)$. As the subroutine of Remove Minimum Bandwidth Constraint in Definition 2 contains the process of Remove Maximum Bandwidth Constraint in Definition 1, the complexity of Remove Minimum Bandwidth Constraint in Definition 2 is $O(KN_Q \log_2 N_Q \times N_Q \log_2 N_Q) = O(K(N_Q \log_2 N_Q)^2)$.

In summary, the complexity of the proposed MPBA algorithm is $O(K(N_Q \log_2 N_Q)^2 + N_Q N_L)$, which satisfies the requirement of the low computational complexity and the real-time bandwidth allocation.

IV. SIMULATION ANALYSIS

A. Simulation Scenarios and Parameter Settings

As is shown in Figure 2, an OPNET based simulation scenario of MSBN is built to verify the MPBA scheme in this paper.

The constellation of this scenario is composed of six MEO satellites, with the height of 12,800km and 0° inclination, which means that the propagation delay of satellite-ground link is $56ms$ and inter-satellite link is $64ms$. For each satellite, they contain 4 satellite-ground links and 2 inter-satellite links. For every satellite-ground link, there are 20 users to be allocated bandwidth resources. Traffic parameters of these users are shown in Table I. The conversation and streaming service

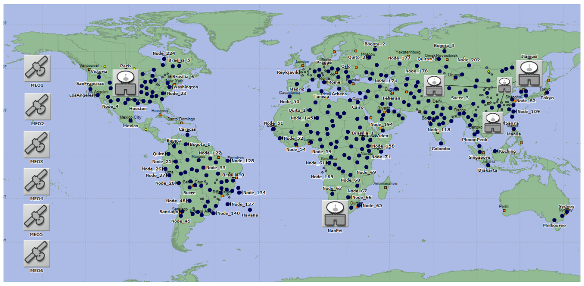

Figure 2. The Simulation Scenario of MSBN

are based on IP protocol, while interactive and background service are based on TCP protocol. We set that the number of inter-satellite route hops for every user is 3, so the inherent propagation delay for every user is $56 \times 2 + 64 \times 3 = 304ms$.

In the process of solving the Lagrangian relaxation solution, the initial iteration step of the projection gradient descent method $\mathbf{r^0 = 0.5}$, the attenuation factor $\mathbf{T = 0.75}$.

TABLE I. THE TRAFFIC PARAMETERS OF USERS

User ID	Traffic Type	Priority	Requests(bps)	Minimums(bps)
1-5	Conversation	4	25,600	25,600
6-10	Streaming	3	25,600	12,800
11-15	Interactive	2	19,200	9,600
15-20	Background	1	6,400	3,200

B. *Simulation Results*

The performance of the end-to-end delay and the system utility in the traditional single resource pool framework based bandwidth allocation algorithm [4] and our MPBA algorithm are analyzed in this section.

Let C_{s-g} and C_{s-s} be the bandwidth capacity of the satellite-ground link and the inter-satellite link for every satellite.

For $C_{s-g} = 307,200bps$, which means that bandwidth resources of satellite-ground links are adequate for bandwidth requests of 20 multimedia users. Take the bandwidth capacity of inter-satellite C_{s-s} as a variable, which changes from $7 \times C_{s-g}$ to $13 \times C_{s-g}$, the performance of the end-to-end delay is shown in Figure 3. When $C_{s-s} \geq 12 \times C_{s-g}$, the resource capacity of inter-satellite links are sufficient to meet maximum bandwidth requests of 20 users, so the end-to-end delay is equal to the inherent propagation delay $(304ms)$ for both the traditional algorithm and the MPBA algorithm. However, when $C_{s-s} < 12 \times C_{s-g}$, it shows that the MPBA improves significantly on the end-to-end delay over the traditional algorithm since limited resource capacities of inter-satellite links are taken into consideration in the process of the bandwidth allocation. Moreover, the more scarce the resource of the inter-satellite link is, the most significant the end-to-end delay improvement could be in the MPBA scheme.

The performance of the end-to-end delay for $C_{s-g} = 204,800bps$, in which the resource capacity of every satellite-ground link meets minimum bandwidth requests of 20 users, is shown in Figure 4. And $C_{s-g} = 153,600bps$, in which resource capacities of satellite-ground links could not meet the minimum bandwidth request of every user, is shown in Figure 5. Both Figure 4 and Figure 5 verify that the MPBA scheme outperforms over the traditional algorithm on the end-to-end delay for MSBN system.

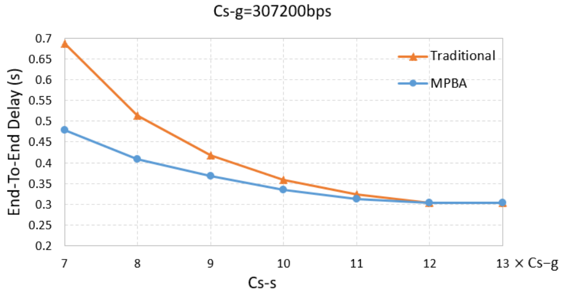

Figure 3. The End-to-End Delay for $C_{s-g} = 307,200bps$

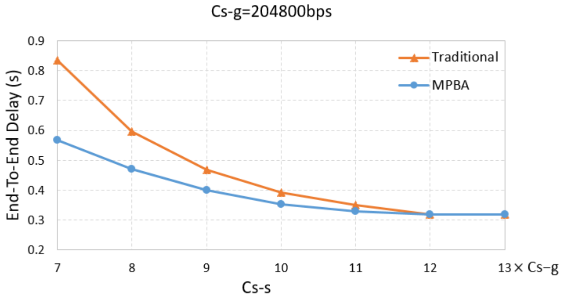

Figure 4. The End-to-End Delay for $C_{s-g} = 204,800bps$

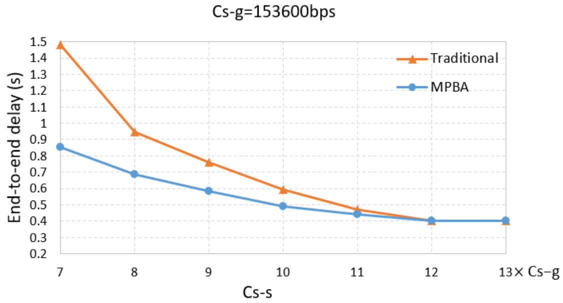

Figure 5. The End-to-End Delay for $C_{s-g} = 153,600bps$

The system utility, which is computed in (1), for $C_{s-g} = 307,200bps$ is shown in Figure 6. Thanks to the consideration of the limited resource capacity in every link, the resource manager would not accept too much network traffics in the MPBA scheme. However, the traditional algorithm would accept as much traffics as the satellite-ground link could afford, with the ignorance of traffic carrying capacities on inter-satellite links, which could cause congestion in the system. For lossless protocol based traffics, there would be much retransmission in the traditional algorithm, which results in the repeated occupancy of system resources and the aggravation of congestion. As a result, the system utility of the traditional algorithm would be lower than our MPBA scheme. As is shown in Figure 6, the less resource capacities of inter-satellite links, the more improvement on the system utility of the MPBA algorithm than the traditional one.

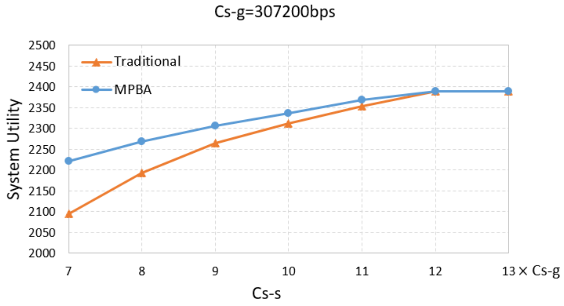

Figure 6. The System Utility for $C_{s-g} = 307,200bps$

V. CONCLUSION

The contributions of this paper are a multi-pool framework for MSBN system along with the game theory based bandwidth allocation algorithm that takes different QoS bandwidth demands of multimedia services into account.

Unlike traditional single satellite-ground link based approaches, the dynamic bandwidth capacities of whole links are taken into consideration in the MPBA scheme, with satellite-ground links and inter-satellite links included. This results in the effective improvement in the end-to-end delay, increased the robustness to the dynamic change of bandwidth resources in different links. Then, depending on the proposed multi-pool framework, the game theory based bandwidth allocation algorithm takes the different bandwidth demands of multimedia services into consideration, which meets the requirement of the low computational complexity of the on-board process.

Comparing with the traditional algorithm, simulation results show that a good usage of the system resource and a significant improvement of the end-to-end delay could be achieved. Moreover, the more unbalanced the resources of inter-satellite links and satellite-ground links are, the most significant the improvement could be in the MPBA scheme.

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