

# Load Balancing in Multi-beam Satellite Systems

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## I. Introduction

We propose an approach to **balance the load on spot-beam queues** in a multi-beam broadband satellite system that supports both unicast and multicast flows. We consider a satellite communication system, where users access the terrestrial network through the network operations center (NOC). The satellite supports **multiple spot-beams** and **on-board packet switching** technologies that allow transmission of data to multiple users in multiple spot-beam locations (Figure 1).

In this system, packets of several active flows are queued at the NOC buffer. NOC forwards the packets to the satellite at a rate dictated by the uplink capacity of the system. An on-board processor and switch store the packets in one or multiple spot-beam queues:

- A packet belonging to a **unicast flow** is forwarded to a **single beam queue**, corresponding to the location in which the user resides.
- In a **multicast flow**, users may reside in multiple beam locations, and packets need to be duplicated and stored in **multiple spot-beam queues**.

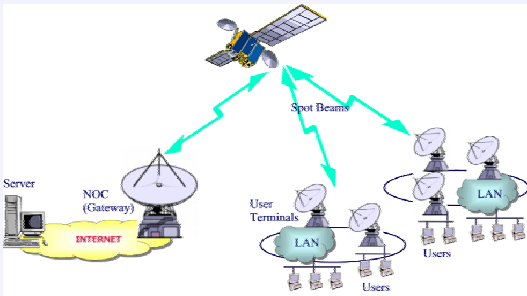


Figure 1: Network Topology

## II. Problem Statement

Depending on the **type of the flows** and the **distribution of users** across spot-beam coverage areas, the load on every spot-beam queue could be different. Therefore, the following problems have to be addressed:

- How to share the service rate of a spot-beam queue among the flows belonging to the same beam?
- How to adjust the flow rates at the NOC, such that spot-beam queues will not overflow?

In a typical system, **spot-beam queues share the access to antennas**, transmitting in bursts when the connection is realized. If all spot-beam queues were given **equal time-shares**, the amount of data that could be transmitted by a flow would be dictated by its **minimum service rate** among the queues which it belongs to. A **high load variation** among queues would **under-utilize** those queues that could serve the flow at a higher rate. This generates the following problem:

□ We need to find an **optimal way to share the downlink capacity** of the system among spot-beams so that the **queues are utilized efficiently**, and **flows are served at maximum sustainable rates** at the NOC.

## III. Problem Formulation

Each flow  $f_i, i \in \{1, 2, \dots, L\}$ , is assigned a time-share  $w_{ij}$  of the burst duration of the beam  $B_j, j \in \{1, 2, \dots, M\}$ , based on the **load of the queue** and the **type of the flows** forwarded to the queue.  $M$  beams share access to  $N$  antennas, and the beam  $B_j$  gets a time-share  $\gamma_j$  of the frame duration of the antenna it is assigned to.

□ Packets of flow  $f_i$  could be served at a **maximum rate** of  $\sigma_{ij} w_{ij} \gamma_j R_d$  at beam  $B_j$ , where  $R_d$  is the downlink rate of the antenna.

□ The input rate of the flow  $f_i$  at the NOC should satisfy  $\rho_i \leq \min_j \sigma_{ij}$  in order to **avoid overflowing** any of the on-board spot-beam queues.

□ If  $\gamma_j \leq \gamma_{j'}$ , then the maximum sustainable rate of a flow at the NOC is determined by  $\min_j w_{ij}$  for flow  $f_i$ . The  $w_{ij}$  values are solely determined by the load of the queue and the type of the flows, hence a high load variation among queues could significantly affect the rate at which the flow is served.

Therefore, we want to find the **optimal vector**  $\gamma = \{\gamma_1, \dots, \gamma_M\}$  that would **minimize the variance** of the rates of a flow across beams for all flows:

$$\gamma = \arg \min_{\gamma} \sum_j \sigma_{ij}^2 \gamma_j^2$$

where  $\sigma_{ij}^2 = \frac{1}{N_j} \sum_{j \in A_n} s_{ij}(\sigma_{ij} \gamma_j)^2$ ,  $\sigma_{ij} = \frac{1}{N_j} \sum_{j \in A_n} s_{ij} \gamma_j$ ,  $s_{ij} = \frac{f_i \gamma_j}{\sum_{j \in A_n} f_i \gamma_j}$ , and  $N_j$  is the number of beams flow  $f_i$  is forwarded to such that:

$$\sum_{j \in A_n} \gamma_j = 1, \text{ for } n \in \{1, 2, \dots, N\}, \forall n, j$$

where  $A_n$  is the set of beams accessing antenna  $n$ .

## IV. Solution

The solution vector,  $\gamma = \{\gamma_1, \dots, \gamma_M\}$  is given in close form:

$$\gamma_j = \frac{1}{\sum_{j \in A_n} \frac{1}{\sigma_{ij}^2}}$$

## V. Results

Figure 2(a) shows the locations of the **48 spot-beams** in two polarizations over the United States for a satellite system. Figure 2(b) shows the probability distribution of a flow being forwarded to a beam, based on the total population in the beam coverage area. The 48 beams share

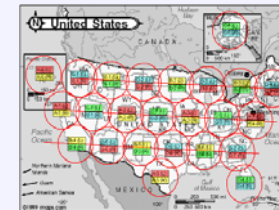


Figure 2(a): Beam Locations

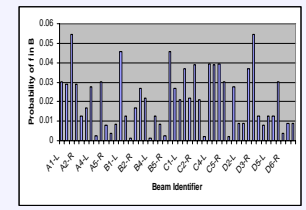


Figure 2(b): Probability of  $f \in B$

ANT1	ANT2	ANT3	ANT4
D1-L	D1-R	B1-L	B1-R
D2-L	D2-R	B2-L	B2-R
D3-L	D3-R	B3-L	B3-R
D4-L	D4-R	B4-L	B4-R
D5-L	D5-R	B5-L	B5-R
D6-L	D6-R	B6-L	B6-R
D7-L	D7-R	A1-R	C1-L
C1-R	A1-L	A2-R	C2-L
C2-R	A2-L	A3-R	C3-L
C3-R	A3-L	A4-R	C4-L
C4-R	A4-L	A5-R	C5-L
C5-R	A5-L	A6-R	
	A6-L		

Table 1: Antenna Sharing

the access to the 4 on-board antennas as shown in Table 1. In order to evaluate the effectiveness of our optimization, we create unicast and multicast flows between the NOC and the spot-beam locations using the distribution function given in Figure 2(b). The optimal time-share of each beam is calculated, and the sustainable rate of every flow is compared to the case when all beams get equal time-share of the antenna. The weight  $w_{ij}$  of a flow  $f_i$  in beam  $B_j$  is determined by  $n_{ij}$ ,

$$w_{ij} = \begin{cases} 0, & \text{if } n_{ij} = 0 \\ \frac{1}{\sum_{j \in A_n} (1 + \log(n_{ij}))}, & \text{if } n_{ij} > 0, \forall n, j \end{cases}$$

Table 2 shows the results when the system is loaded with  $L_u = 250$  active unicast flows and  $L_m = 35$  active multicast flows as averaged over 500 session configurations.

$L_u$	250	250	250	250	250	250	250
$L_m$	5	10	15	20	25	30	35
$R_1$	39.06%	41.08%	42.36%	43.46%	44.24%	44.87%	45.61%
$R_2$	13.80%	15.66%	15.42%	14.98%	14.68%	14.51%	14.43%
$N$	64.36%	72.40%	77.77%	80.30%	81.55%	82.30%	82.69%
#users	395.54	536.97	682.31	825.91	968.07	1112.80	1256.40

Table 2: Analysis Results

In Table 2,  $R_1$  is the average rate increase experienced by all active flows after optimization.  $R_2$  denotes the average increase in the total system throughput at the NOC, and  $N$  is the percentage of users that experienced a rate increase. Last row of Table 2 gives the average number of users in all active flows. We observe that this optimization in general benefits a large percentage of the active flows and results in 13-15% improvement in the total system utilization. The improvement is more pronounced when number of multicast flows increases.

### REFERENCES:

[1] G. Akkor, J. S. Baras, and M. Hadjithodosiou, "An optimization-based approach to flow control and resource allocation problem in satellite communication systems," will appear in *Proceedings of AIAA ICSSC 2004*, May 2004, Monterey, CA.