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.

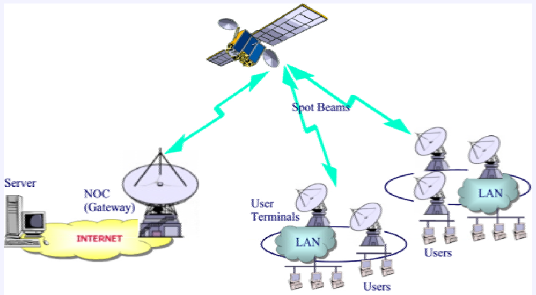

Figure 1: Network Topology

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 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 $f_i, i = 1,2,\ldots,L$, is assigned a time-share w_{ij} of the burst duration of the beam $B_j, j = 1,2,\ldots,M$, 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 γ_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 $\lambda_{ij} = w_{ij}\gamma_j R_d$ 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 $\lambda_i = \min_j\{\lambda_{ij}\}$ in order to avoid overflowing any of the on-board spot-beam queues.

❑ If $\gamma_1 = \gamma_2 = \ldots = \gamma_M$, 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 $\gamma^* = (\gamma_1, \ldots, \gamma_M)$ that would minimize the variance of the rates of a flow across beams for all flows:

$$\gamma^* = \operatorname*{argmin}_{\gamma} \sum_{i=1}^{L} \sigma_i^2$$

where $\sigma_i^2 = \frac{1}{N_i}\sum_{j=1}^{M} s_{ij}(\lambda_{ij} - \bar{\lambda}_i)^2$, $\bar{\lambda}_i = \frac{1}{N_i}\sum_{j=1}^{M}\lambda_{ij}$, $s_{ij} = \begin{cases} 1, & f_i \in B_j \\ 0, & f_i \notin B_j \end{cases}$, and N_i is the number of beams flow f_i is forwarded to such that :

$$0 \le \gamma_j \le 1$$

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

where A_n is the set of beams accessing antenna n.

IV. Solution

The solution vector, $\gamma^* = (\gamma_1, \ldots, \gamma_M)$ is given in close form:

$$\gamma_j = \frac{1}{a_j \sum_{k=1}^{M} \frac{1}{a_k}}, \text{ where } a_j = \sum_{i=1}^{L} \left\{ \frac{2(N_i - 1)}{N_i^2} w_{ij}^2 \right\}.$$

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 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}, which is the number of receivers of the flow in B_j:

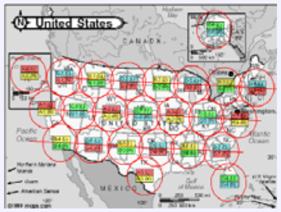

Figure 2(a): Beam Locations

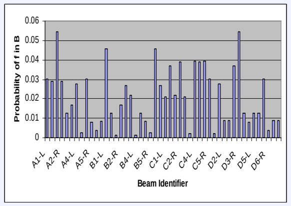

Figure 2(b): Probability of $f \in B$

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

$$w_{ij} = \begin{cases} 0, & \text{if } n_{ij} = 0 \\ \dfrac{1 + \log(n_{ij})}{\sum_{i=1}^{L}(1 + \log(n_{ij}))}, & \text{if } n_{ij} > 0, \ \forall i, j \end{cases}$$

Table 2 shows the results when the system is loaded with $L_u = 250$ active unicast flows and $L_m = 5 - 35$ 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. Hadjitheodosiou, "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.