Connectivity Planning and Call Admission Control in an On-board Cross-connect Based Multimedia GEO Satellite Network

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***Abstract* — This paper addresses end-to-end connectivity planning and call admission control for a high capacity multi-beam satellite network with on-board cross-connectivity. On-board satellite switching is a technology designed to offer multi-media services, especially in demographically dispersed areas. Nevertheless, full on-board switching techniques are far from maturity. Their implementations have been proven expensive and difficult. There are also high risks involved in launching satellites for the stationary orbit surrounding the earth. As a substitute, a satellite network with on-board cross-connect is devised in this paper. Connectivity planning and call admission control mechanisms associated with such a network are also presented. Simulation studies are conducted to show the effectiveness of the proposed mechanisms.**

Keywords-GEO satellitet; on-board switching, on-board cross-connect, call admission control, connectivity planning.

I. INTRODUCTION

Digital satellite systems are viewed as viable service vehicles for traditional entertainment broadcasting. They are also potential supplements for the existing wire-line and legacy networks in meeting the increasing demand for Internet and multimedia oriented broadband access at demographically dispersed areas. Many system proposals promising high capacity and ease of access require advanced switching technology and signal processing on-board the satellite(s) ([1], [3]). One solution is based on a geo-synchronous (GEO) satellite system equipped with on-board processing and on-board ATM switching ([1], [3], [6]). While this system aims to maximize the number of simultaneous users, it also requires very effective medium access control (MAC) layer protocols for connection admission control (CAC) algorithm, as well as complicated on-board switching facilities ([2], [4], [5]). The satellite network described in this paper features a new full beam-to-beam connectivity on-board the GEO satellite while enabling a regional early entry to the market. Unlike on-board switching techniques, the on-board connectivity information of the GEO satellite is pre-configured and uploaded. The intelligence for the on-board switching functionalities are moved to the gateways on the ground, which significantly reduces the risks associated with on-board processing. The concept is based on implementing connectivity at the physical layer via pre-provisioning. ATM connections are subsequently set up in real-time within these physical paths through call admission control procedures. Setting up connections this way simplifies the on-board functionalities but still guarantees no collision and efficient utilization on the precious MAC layer resources.

This paper is organized as follows. In section 2, a GEO-based high capacity multimedia satellite network with on-board cross-connectivity is presented. The return link and forward link access schemes are described. Section 3 addresses the on-board connectivity planning and modeling issues for the satellite systems. The detailed call admission control procedure is explained in section 4. Section 5 presents the simulation results and section 6 concludes the paper.

II. GEO SATELLITE NETWORK ARCHITECTURE

Figure 1 illustrates the architecture of the multimedia GEO satellite network with on board cross-connectivity. The satellite core is a cross-connect, which provides connectivity from beam to beam. There are two different types of access units in the network. User terminals connect individual users to the satellite while gateways connect the satellite network to the terrestrial networks.

There are in total N spot beams covered by the GEO satellite and there is a gateway associated with each beam. A return channel is defined as the path from the user terminals to the satellite to the gateways. A forward channel is defined as the path from the gateways to the satellite to the user terminals. The return link access scheme is based on MF-TDMA, providing access from terminals on a mixed time and

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frequency-shared basis as shown in Figure 2. The terminals access narrow-band carriers. Each narrow-band carrier occupies a bandwidth of *g Khz* or α *kbps* equivalently, and is time-slotted on single ATM cell transmission. There are in total *A* time slots per carrier and *B* carriers per superframe in the return channel. The access scheme of the forward link from the gateways to the terminals is based on TDM mode at a much higher rate. Each superframe consists of *A* frames. Configuration for the on-board cross-connect are managed by the Network Control Center (NCC) on a pseudo-static basis as shown in the next section, while ATM connection setup and resource management for the physical paths are under gateway's control.

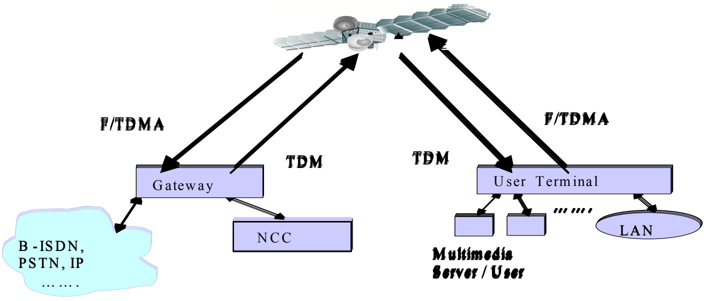

Figure 1. Network architecture for the Satellite network with on-board cross-connect

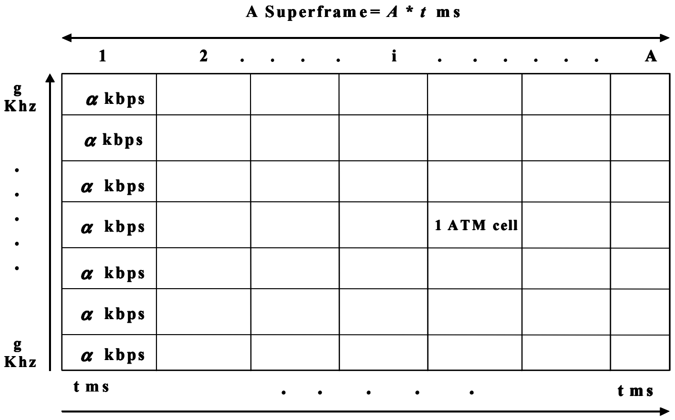

Figure 2. Return channel MF-TDMA frame structure

III. ON-BOARD CROSS-CONNECTIVITY PLANNING

Under careful provisioning, both return channel and forward channel connectivity provide full beam-to-beam connections in both directions without any collisions. Figure 3 shows the concept for return channel on-board connectivity. Each little trapezoid in the figure represents an entire *g Khz* carrier. Return channel connectivity is provided at the granularity of one single carrier and all the time slots of one carrier in a particular source beam are assigned to the same source destination beam. The total *B* return channel carriers in each source beam are partitioned among different destination gateways based on the estimated traffic demand. The gateway in each beam needs to maintain two return channel frequency plans:

1. An uplink frequency plan, consisting of a number of carriers and their assigned destination beam.
2. A downlink frequency plan, consisting of a number of carriers and their associated originating source beam.

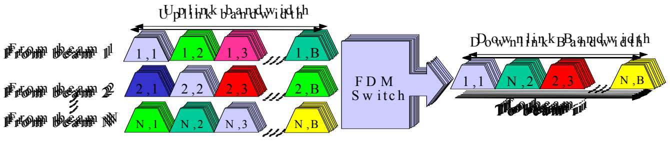

Figure 3. Return channel on-board connectivity

The concept of on-board connectivity for the forward channel is expressed in Figure 4. In the forward channel, routing from a given gateway to the terminals is performed by on-board switching of the uplink frames according to a cross-connect matrix. The granularity of forward channel connectivity is a single frame per superframe. Any single frame in the uplink TDM carrier from a particular gateway can be assigned to the same frame in the downlink TDM carrier of any beam. One cycle of the forward channel connectivity consists of *A* connectivity patterns, with each representing the instantaneous full gateway-to-beam connectivity for each frame period.

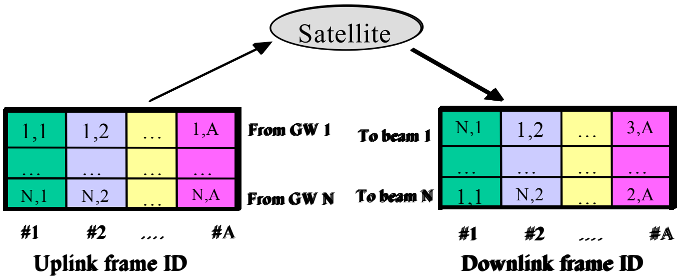

Figure 4. Forward channel on-board connectivity

Both return channel and forward channel cross-connectivity patterns are computed by the NCC according to the traffic demands and are uploaded to the satellite then. Unlike on-board satellite switching, on-board cross-connectivity cannot be dynamically changed. Nevertheless, the simulation results show that the pseudo-static on-board cross-connectivity is still capable of achieving satisfactory network performance with the existence of dynamic beam-to-beam traffic demands.

IV. CALL ADMISSION CONTROL PROCEDURE

Any connection initiated by satellite users is assumed to end in the terrestrial network. For a satellite connection, the home gateway (HGW) is the gateway in the source beam, and the destination gateway (DGW) is the gateway that connects the satellite user to the terrestrial destination. CAC procedure is responsible for selecting the DGW that 1) has enough bandwidth to support a connection request; 2) results in the shortest distance to the connection's terrestrial destination.

The detailed CAC procedure flow chart is depicted in Figure 5, in which the block marked in dark represents the CAC bandwidth allocation scheme. For the ATM connections accepted by the CAC procedure, the CAC controllers in the HGW and DGW need to statically allocate to each connection *j* an amount of return channel resources SRr_j and an amount of forward channel resources SRf_j. The amount of resources statically allocated depends on the connection type (i.e. CBR, rt-VBR, nrt-VBR, ABR, or UBR), traffic descriptor and requested QoS ([4]). In addition to the resources statically allocated, the CAC controllers also 'book' for a connection *j* two resources: BRr_j for the return channel and BRf_j for the forward channel ([5]). The value of the booked resources also depends on the connection type, traffic descriptor and requested QoS. The CAC controllers in the HGW and DGW grant admission to connection *j* leaving source beam *a* and destined to beam *b*, only if the sum of what is to be statically allocated to *j* and what is to be booked for *j* is less than the total provisioned return channel capacity Cr_{ab} from beam *a* to beam *b*, and the total provisioned forward channel capacity Cf_{ba} from beam *b* to beam *a*, minus the sum of the already allocated capacity and minus the sum of the booked capacity for all ongoing calls k on the links, i.e.,

$$SRr_j + BRr_j + \sum_k SRr_k + \sum_k BRr_k \le Cr_{ab} \quad (1)$$

$$SRf_j + BRf_j + \sum_k SRf_k + \sum_k BRf_k \le Cf_{ba} \quad (2)$$

In addition to the above two constraints, we have a third CAC constraint due to the fact that individual users are only equipped with small antennas:

No terminal is allowed to transmit simultaneously on two different carriers. (3)

Connection *j* is accepted only if all three constraints are satisfied. For a high capacity broadband satellite network described in this paper, analytically solving the optimal CAC problem with the above three constraints involves a very large number (up to ten thousands) of simultaneous ordinary differential equations ([8]), which is infeasible by the current computing power. In the next section, we use simulation to evaluate the operational performance of the proposed CAC algorithm in a satellite network with on-board cross-connectivity.

V. SIMULATIONS AND RESULTS

In this section, detailed simulation modeling and performance evaluation results are provided. The simulations are performed in OPNET.

A. Traffic modeling

The simulations assume a cross-connect satellite system with 3 beams. In Table 1, five typical satellite applications are identified to represent a good mix of traffic type, market segmentation and connectivity ([7]). Each application is modeled with two different levels: session level and burst level ([4]). Both session duration and session inter-arrival time are exponentially distributed. The burst level is modeled as on-off sources with different on/off distributions for different applications. The session level characteristics for the five applications are listed in Table 1 and Table 2. The burst level characteristics are listed in Table 3. The burst level parameters are the same for all the beams while session level parameters are different from beam to beam. This provides each beam a different traffic volume and a different mix of five applications.

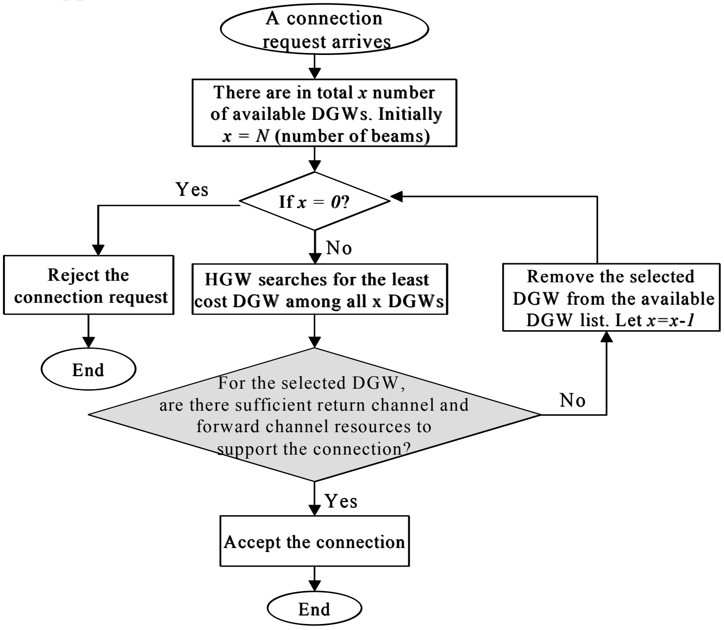

Figure 5. Proposed Call Admission Control flow chart in a satellite network with on-board cross-connect

Beam	Relative Beam Volume	Shopping	News	Telephony	Web Access	Business Services
1	91%	36	845	3,332	5,026	16,753
2	74%	10	606	2,230	3,001	11,405
3	98%	17	1,179	5,180	7,269	24,251

TABLE 1. BEAM VOLUME AND HOURLY SESSION ARRIVAL RATE

Application	Session Duration (Minutes)	ATM transfer capability
Shopping	60	ABR
News	20	VBR
Web Browsing	15	ABR
Telephony	3	CBR
Business Services	1	ABR

TABLE 2. APPLICATION USAGE CHARACTERISTICS

Application	Return PCR (Kbps)	Return ECR (Kbps)	Return SCR (Kbps)	For - ward PCR (Kbps)	For-ward ECR (Kbps)	For ward SCR (Kbps)
Shopping	64	3.2	2.6	384	19.4	15.4
News	64	3.6	3.2	128	7.2	6.4
Web Browsing	16	1.8	1.4	384	43.4	33.8
Telephony	32	18	17	32	18	17
Business Services	384	22	18	384	22	18

TABLE 3. APPLICATION BURST LEVEL CHARACTERISTICS

B. Connectivity modeling

In the simulations, we assume all the services are initiated by the satellite users and destined somewhere in the terrestrial network. Thus the services can be provided with just one hop to the satellite. The beam-to-beam traffic demand on the return channel is shown in Table 4. The forward channel traffic distribution is just the transpose of the return channel traffic distribution. For example, the amount of traffic leaving beam 1 to DGW 3 is 38% of total traffic leaving beam 1. Then the amount of forward traffic from GW 3 to beam 1 is also about 38% of total traffic destined to beam 1. There is a two-step-estimation procedure that leads to Table 4 and Table 5.

a) Estimation on the traffic distribution between satellite users and terrestrial users.

b) Estimation on satellite users to DGW traffic distribution by using least cost routing criteria.

The return channel and forward channel resources are then partitioned correspondingly. For example, 38% of uplink return channel carriers in beam 1 and 38% of downlink return channel carriers in beam 3 are assigned to the traffic leaving from beam 1 to DGW 3. 38% of uplink forward channel frames in beam 3 and 38% of downlink forward channel frames in beam 1 are assigned to the traffic from DGW 3 to terminals in beam 1. Thus the connectivity can be configured based on resource partition of return channel carriers and forward channel frames.

Beam	1	2	3
1	42%	20%	38%
2	30%	37%	34%
3	28%	44%	28%

TABLE 4. RETURN CHANNEL TRAFFIC DISTRIBUTION

Beam	1	2	3
1	42%	30%	28%
2	20%	37%	44%
3	38%	34%	28%

TABLE 5. FORWARD CHANNEL TRAFFIC DISTRIBUTION

C. Results and discussions

The following measurements are obtained from the simulations:

- Beam CAC commitment: the number of time slots that have been statically reserved or booked through CAC over the total number of time slots in MF-TDMA uplink. This measurement provides good estimations on billable bandwidth and revenue.
- Beam call setup time: the time it takes for a user to receive the CAC response since it issues the CAC request.
- Indirect call probability: the ratio of the number of calls which cannot be assigned resources at CAC level for the default ‘best’ gateway, but which can be accepted by using available resources via another gateway, to the total number of calls accepted. This measurement reflects the efficiency of the cross-connectivity.
- Call blocking probability: the ratio of the number of blocked sessions of each type of application to the total number of sessions requesting connections from that type of application.

The first simulation estimates the performance of the proposed CAC algorithm by assuming an ideal match between the traffic distribution and connectivity provisioning, as shown in Table 4 and Table 5. Figure 6 indicates 58%, 38% and 84% CAC commitments for beam 1, 2, 3, respectively. Table 6 shows that only telephony in beam 3 experiences a nonzero call blocking probability. About 0.024% Telephony calls are rejected. The blocking ratio for each application is an increasing function of its session arrival rate and requested bandwidth. There is no call blocking observed in beam 1 and beam 2 given their low CAC commitments at 58% and 38%. Notice that beam volumes are 91%, 74%, and 98% for beam 1, 2, 3. The reason why we observe low CAC commitments and low call blocking ratios with such high beam volumes is because we choose high percentage of ABR type of traffic in the traffic mix. Figure 7 shows that the indirect probability in simulation 1 is only 1e-05, which indicates only 0.005% of overall accepted calls select the DGWs that are not on the best routes. With ideal connectivity planning assumption in simulation 1, low indirect call probability is what we expected. Indirect call probability is very important for the satellite network we investigate because 1) low indirect call probability results in fast call set up for majority of the call requests; 2) it indicates how good the current cross-connectivity planning is. Figure 8 gives the call set up time, which is 529.75ms in beam 1, 528.55ms in beam 2, 531.80ms in beam 3. In the simulations, we assume that GEO satellite propagation delay is about 250ms, HGW CAC process takes 3.3ms, HGW-DGW communication takes 20ms, DGW CAC process takes 3.3ms. Thus for a direct call, the CAC setup time should be about 250*2+3.3+20+3.3 =526.6ms. For an indirect call which selects the *ith* least cost gateway, its call setup time is 526.6ms+26.6**(i-1)* ms. Due to low indirect call probability in simulation 1, the call set up time in all three beams is very close to the minimum value 526.6ms.

To further investigate the impact of cross-connectivity on the network performance, the second simulation assumes that the connectivity does not match with the traffic distribution. We keep connectivity matrix the same as in simulation 1. The new traffic distribution is generated based on Table 7. All other parameters are still the same as those in simulation 1. Figure 9 shows that the indirect call probability increases significantly to 22% in this case. The call set up time shown in Figure 10 also increases to 535.2ms, 529ms, and 562ms for beam 1, 2, and 3, correspondingly. Since call setup time is dominated by the satellite propagation delay, indirect calls do not significantly increase the call setup time percentage-wise. Due to the mismatch between the connectivity and traffic demand distribution, there are a multitude of indirect calls. Connectivity based on Table 4 and 5 allocates 42% total beam 1 bandwidth to DGW 1. However, Table 7 indicates that, in reality, 55% of total traffic leaving beam 1 considers DGW 1 as the least cost route gateway. Thus at least (55%*91%-42%)/91%=8.9% of total traffic leaving beam 1 becomes indirect calls. For the same reason, at least (55%*74%-37%)/74%= 5% of total traffic leaving beam 2 and (70%*0.98-28%)/98%=41.4% of total traffic leaving beam 3 contributes to indirect calls. Thus the overall indirect call probability should be no less than:

$$\frac{8.9\%\times 91\% + 5\%\times 74\% + 41.4\%\times 98\%}{91\% + 74\% + 98\%} = 19.9\%$$

The actual indirect call probability is 22%. There are some other indirect calls that are not counted in the above formula. For example, 41.4% indirect calls in beam 3 mentioned above may use GW 1 (or 2) as their second least cost GW, which may force part of beam 3 to GW 1 (or 2) traffic in Table 7 to become indirect calls too. In spite of high indirect call probability in simulation 2, it is very promising to find that CAC commitments and call blocking ratios are still the same as those in simulation 1. This observation is justified by the followings. The beam volumes in both simulations are the same. The total bandwidth serving the traffic leaving a beam and the total bandwidth serving the traffic destined to a beam are fixed (100%) regardless of traffic mismatch. Traffic mismatch may push some connections to choose non-least cost GW but does not decrease the available resources to the users. Thus the call blocking probability keeps the same.

Based on the results from both simulations 1 and 2, we can safely conclude that satellite networks with on-board cross-connectivity with proposed CAC procedure can provide comparative CAC commitments and call blocking ratios compared with satellite networks equipped with on-board switching. However, since on-board cross-connectivity can not be provisioned dynamically, unavoidable traffic mismatch increases indirect call probability and call setup time. Nevertheless, simulation results show that call setup time in traffic mismatch case is still acceptable.

Application	Call Blocking Probability
Shopping	0.00E+00
News	0.00E+00
Web Browsing	0.00E+00
Telephony	2.40E-05
Business Services	0.00E+00

TABLE 6. CALL BLOCKING RATIOS FOR SIMULATION 1

Beam	1	2	3
1	55%	20%	25%
2	40%	55%	5%
3	5%	25%	70%

TABLE 7. TRAFFIC MISMATCH DISTRIBUTION FOR SIMULATION 2

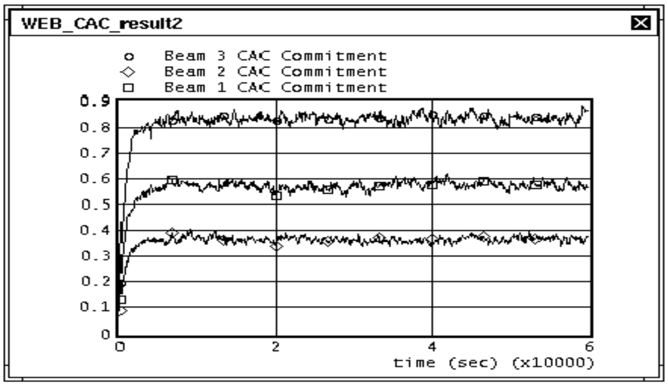

Figure 6. CAC commitments for simulation 1

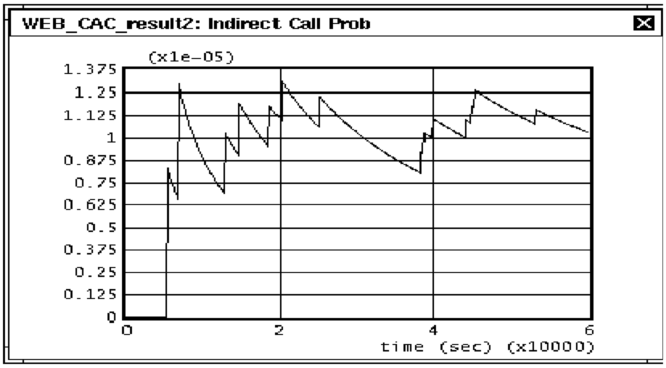

Figure 7. Indirect call probability for simulation 1

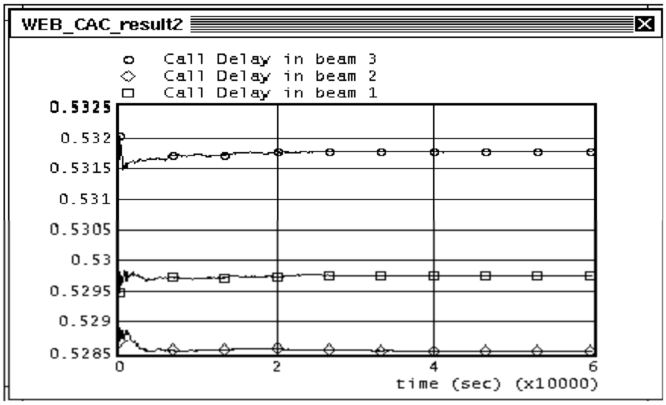

Figure 8. Call set up time in 3 beams for simulation 1

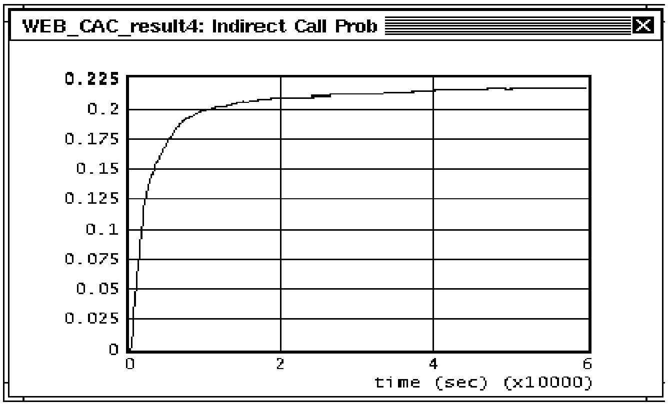

Figure 9. Indirect call probability for simulation 2

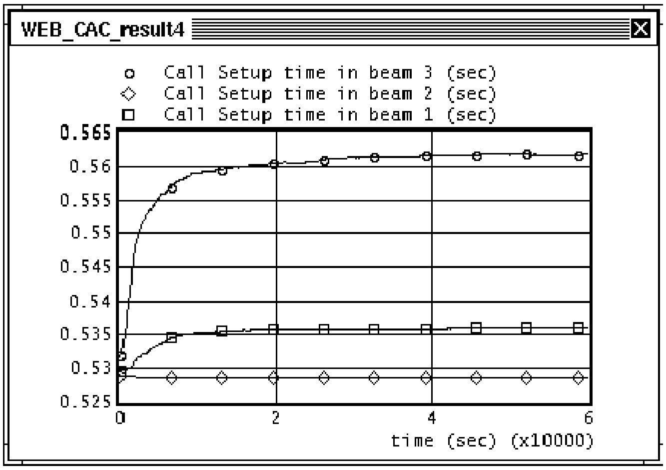

Figure 10. Call set up time in 3 beams for simulation 2

VI. CONCLUSIONS

Broadband satellite networks present unique challenges in system design and traffic management related to service quality and revenue generation. This paper presents detailed traffic management and simulation modeling approaches for a specific satellite network, which, instead of having on-board switching, implements on-board cross-connect and enables an early entry to the market due to reduced risk and complexity on-board the satellite. An end-to-end CAC procedure for the on-board cross-connect based satellite network is proposed in the paper. The simulation studies investigate important design and performance issues such as connectivity planning, call blocking ratios, indirect call probability, and CAC commitments. The results demonstrate that an on-board cross-connect based GEO satellite network with the suggested CAC algorithm can provide satisfactory CAC performance and it can be safely considered as a viable substitute to the on-board switching technique for the purpose of low risk and less complexity.

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