A Connection Admission Control Algorithm For Low Earth Orbit Satellite Networks

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In this paper, a connection admission control algorithm, referred to as the Geographical Connection Admission Control (GCAC) algorithm, is introduced to handle the spotbeam handovers in the low earth orbit (LEO) satellite networks. Spotbeam handovers occur frequently because of the small spotbeams and high satellite speed. The GCAC algorithm admits a new call into the network only if the expected handover call blocking probability of the new and the existing calls is not increased beyond a system threshold. The algorithm utilizes the deterministic satellite movement pattern and the user locations to estimate the expected handover call blocking probability. The experimental results show that the algorithm limits the handover call blocking probability and can handle nonuniform traffic distribution over the coverage area of the network.

Keywords: handover, low earth orbit satellites, connection admission control, satellite communications.

I. Introduction

Low earth orbit (LEO) satellites circulate the Earth at altitudes from 500 to 1500 km. This low altitude results in low propagation delay, low power requirements in the user terminals and the satellites, and efficient spectrum utilization using small coverage area for each satellite. However, a number of mobility problems should be solved in order to have feasible implementations of the LEO satellite networks. The satellites located at the low earth orbits move with respect to a fixed observer on the Earth surface. As a result, the coverage areas of the LEO satellites, which consist of small cells referred to as *spotbeams*, are not stationary. To ensure that the ongoing calls are not disrupted as a result of the satellite movement, calls should be transferred or *handed over* to new spotbeams during their lifetimes.

A spotbeam handover, as depicted in Figure 1, involves the release of the user links of the handover terminal in the current spotbeam and the allocation of new user links in the new spotbeam. The handover call might be blocked if the required resources are not available in the new spotbeam. Spotbeam handovers occur frequently because of the small spotbeams and high satellite speed. As an example, in a typical system, average residency time in a spotbeam is in the order of a minute [4]. There is a need for a mechanism to ensure that the handover call blocking probability is within the tolerable limits for the user satisfaction. Since blocking of a handover call is less desirable than blocking of a new call request, spotbeam handover algorithms give higher priority to handover calls. Handover prioritization techniques such as the use of the guard channels [8], [17], handover queueing [5], handover queueing with dynamic channel allocation [4], and connection admission control algorithms [13], [16] have been studied for non-geostationary satellite networks. The interested reader is referred to [2] for the state-of-the art in handover management in the LEO satellite networks.

In this paper, a connection admission control (CAC) algorithm that limits the handover call blocking probability is described. The outline of the paper is as follows. Section II starts with an explanation of the requirements of a CAC algorithm. Our CAC algorithm is introduced with an example in Section II-A. The analytical details of the algorithm is presented in Section II-B. The performance of the algorithm is investigated for uniform and nonuniform traffic distribution in Section III. Finally, we conclude the paper in Section IV.

II. Geographical Connection Admission Control Algorithm (GCAC)

In terrestrial networks, where communication switches do not move, connection admission control test ensures that the switches in the connection route reserve resources to support the required Quality of Service (QoS) during the connection lifetime. In a LEO satellite network, communication channel between the user terminal and the satellite changes often due to the frequent spotbeam handovers. Thus, the CAC function should ensure that the spotbeams have sufficient resources to support future handover calls. However, it is not efficient to reserve bandwidth in every spotbeam that would possibly be used by a connection in the future because of the large number of spotbeams involved. Our CAC function, which is referred to as the *Geographical CAC* (GCAC) algorithm, utilizes the dynamics of the LEO satellite network in order to limit the handover call blocking probability by reserving bandwidth only in three spotbeams.

The performance of a CAC algorithm is largely affected by the call arrival pattern. As the user terminals are expected to be nonuniformly distributed over the Earth's surface, the traffic load of the spotbeams are expected to be time-varying. The CAC algorithm should be able to cope with this time varying or spatially nonuniform traffic distribution. High satellite speed and large coverage area ease the solution of the spotbeam handover problem, since the user mobility is negligible compared to the satellite speed, i.e., the mobility in the system can be approximated by the deterministic movement of the satellites. As an example, in the Iridium system, the satellites travel with a speed of 26,000 km/h ($\approx$ 8 km/s). The diameter of a spotbeam in the Iridium system is approximately 700 km [7]. Thus, the resource allocation algorithms can utilize this approximation to limit or reduce the handover call blocking probability. The spotbeams of the LEO satellites move along known trajectories on

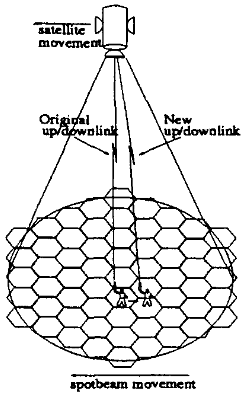

Fig. 1. Spotbeam handover scenario.

the Earth surface with a constant speed. Moreover, the user locations are known since the user terminals, either mobile or fixed, are expected to have Global Positioning System (GPS) receivers [6]. Both the deterministic spotbeam movement and the user location information provide the handover patterns of the user terminals to the system, i.e., future handover behavior of a user terminal would be determined. The GCAC algorithm uses the locations of the user terminals as a basis for its connection admission decisions. Upon a new call arrival, the admission test ensures that the handover call blocking probability of the system, which is also referred to as *Quality of Service* (QoS) in this paper, is below the target blocking rate at all times. The acceptance of a new connection request increases the handover blocking rate in an area swept by the spotbeam that serves the new user. This area is referred to as the *contention area*. The GCAC algorithm ensures that the handover blocking probability averaged over the contention area is less than a target handover blocking probability, which is denoted as P_{QoS} in the remainder of this paper.

A. Algorithm Description

In this section, the basic principles of the GCAC algorithm are introduced with an example depicted in Figure 2. Four spotbeams labeled as B1, B2, B3, and B4 are moving upward as a result of the satellite movement. Figure 2 presents four snapshots taken in the time interval $[t_0, t_3]$. The solid lines show the current positions of the spotbeams while the dashed lines show the initial positions of the spotbeams. At time $t = t_0$ (configuration A), a user terminal, which is denoted as "user X" and is located in spotbeam B1, requires a connection to be set-up[1]. Spotbeam B1 is referred to as the *origination spotbeam* while the spotbeams that will serve user X in the future is referred to as *handover spotbeams*. The call set-up request is rejected, if the origination spotbeam has no available channel for this terminal. Otherwise, the future system configurations are investigated to ensure that the handover call blocking probabilty for the new and the existing calls is not above the target value. User X resides in spotbeam B1 until the handover instant at $t = t_1$ (configuration B). Spotbeam B1 experiences handover requests from the user terminals located in the region swept by itself during its movement in the time interval $[t_0, t_1]$. These terminals are labeled as "handover arrivals" in Figure 2. Also, some user terminals depart from spotbeam B1 due to handover to other spotbeams, and they are labeled as "handover departures" in Figure 2. The GCAC algorithm estimates the handover blocking probability for the handover arrivals in the time interval $[t_0, t_1]$. Since the user locations and spotbeam movement are deterministic, the occurrence times of the handover events for spotbeam B1 are available to the GCAC algorithm. However, it should be noted that a call may depart from the system if the communicating parties terminate their connections. Thus, there is an uncertainty in the handover events, and the GCAC algorithm takes the call statistics into account when determining the system performance in the time interval $[t_0, t_1]$. For each handover event (either arrival or departure), the system state and the handover blocking probability in the contention area are updated. At time $t = t_1$, user X handovers to spotbeam B2. The admission test is continued for spotbeam B2 for the time interval $[t_1, t_2]$ between configurations "B" and "C". Similarly, after time $t = t_2$, admission test is continued with spotbeam B3. The test is performed until the position of spotbeam B3 is identical to the initial position of spotbeam B1 since the relative locations of the spotbeams and the user terminals in the time interval $[t_0, t_3]$ repeats itself periodically. If no QoS violation occurs in $[t_0, t_3]$, no future QoS violation is expected in the future, and thus, the new call is admitted into the network. If a QoS violation occurs, the new call is rejected.

The GCAC algorithm operates similar to an event-driven simulation. Upon a new call arrival, the spotbeams are hypothetically moved along their respective trajectories. During the spotbeam movement, handover arrival and departure events occur. System statistics are updated for every handover event. The time interval between successive events is referred to as the *interevent gap* and is denoted by Δ. Between the handover epochs, a number of calls would have been terminated by the users. Thus, at each event epoch, the system state, which is represented by the number of active calls in the spotbeam, is updated to handle the call terminations. This is followed by the update of the system state according to the handover event.

B. Computational Aspects

The GCAC algorithm estimates the system performance using transient analysis. In our model, the handover call blocking probability is approximated using tail approximation approach in which the spotbeams are assumed to have infinite number of channels. An arriving handover call is blocked with probability $P_{bl} = \sum_{i=N}^{M} p_i$, where M is the number of user terminals located in the spotbeam, and N is the system capacity in channels. Here, p_i represents the probability of having i active calls out of M user terminals located in the spotbeam tested. Note that P_{bl} is the handover blocking probability for a single user terminal in the contention area. However, the admission decision is taken based on the handover blocking probability in the entire contention area, which is determined as

$$P_{bl,CA} = \frac{E\{number\ of\ blocked\ handover\ calls\}}{E\{number\ of\ handover\ calls\}} = \frac{E_{bl}}{E_h} \quad (1)$$

[1]For the sake of presentation clarity, destination terminal is not shown in Figure 2. However, the GCAC algorithm should also be used for the destination terminal.

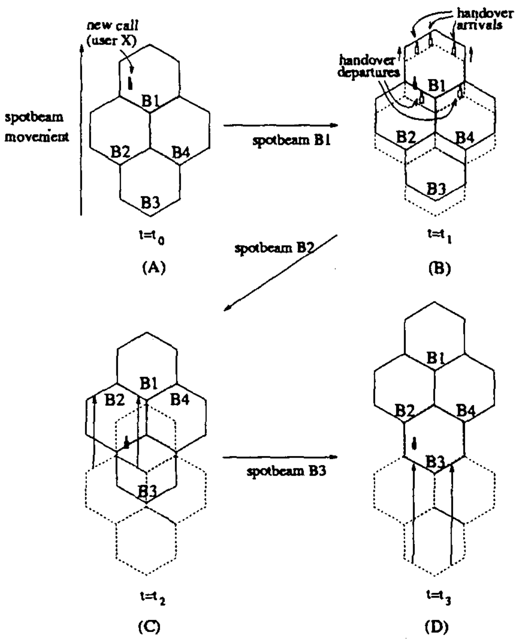

Fig. 2. Example for the GCAC algorithm.

The expected value of the handover arrivals is calculated as:

$$E_h = \sum_{i \in \mathcal{R}} P_{a,i}, \tag{2}$$

where $P_{a,i}$ is the probability that the call i is active at the handover instant, and $\mathcal{R}$ is the set of user terminals that will handover to the spotbeam tested. Similarly, the expected value of the blocked handovers is determined as

$$E_{bl} = \sum_{i \in \mathcal{R}} P_{bl,i} P_{a,i} \tag{3}$$

where $P_{bl,i}$ is the handover blocking probability of call i at the handover instant given that it is active at this instant. Equations (2) and (3) are updated everytime a handover arrival occurs.

Upon a call arrival, the GCAC algorithm is started. The analytical details of the algorithm is as follows.

1. If no channel is available in the origination spotbeam, block the call and terminate the algorithm.
2. Initialize the state variables, i.e., $P_{bl,i} = 0$ for $i \in \mathcal{R}$, $E_h = 0$, $E_{bl} = 0$, $p_i(0) = 0$ for $i \neq M$, and $p_M(0) = 1$ where M is the number of user terminals located in the spotbeam tested.
3. Initialize the system time, i.e., $T = 0$.
4. Determine the next handover event and the interevent gap Δ. Call the handover user as "user H".
5. **System Update:** Update the state probabilities. Since only call terminations could occur between handover events, only downward transitions are possible in the time interval $(T, T+\Delta)$, i.e., some of the active calls would have been terminated by the users.

$$p_j(T+\Delta) = \sum_{i=j}^{M} P_{ij}(\Delta)\, p_i(T) \;\; for \;\; j = 0, 1, ..., M. \tag{4}$$

For exponential holding times with mean $1/\mu$, the state transition probability P_{ij} in (4) is

$$P_{ij}(\Delta) = \binom{i}{i-j} (e^{-\mu\Delta})^j (1 - e^{-\mu\Delta})^{i-j}. \tag{5}$$

Equation (5) is the probability that out of i active calls, $i-j$ calls terminated in a time interval of length Δ, and j active calls remained.
6. Update the system time, i.e., $T = T + \Delta$.
7. **Handover Arrival:** If the event is a handover arrival,
(a) Determine the blocking probability for user H at this instant.

$$P_{bl,new} = \sum_{i=N}^{M} p_i \tag{6}$$

where N is the number of channels of the spotbeam.
(b) If the new call is not located in this spotbeam yet (handover spotbeam), go to Step 7e.
(c) Update the expected number of blocked handovers.

$$E_{bl} = E_{bl} + P_a(1 - P_{bl,H}) P_{bl,new} \tag{7}$$

The term "$P_a(1 - P_{bl})$" is due to the fact that handover blocking can only occur if the call is still active and was not blocked during its earlier handovers.
(d) Increase the number of handover arrivals.

$$E_h = E_h + P_a(1 - P_{bl,H}) \tag{8}$$

(e) Update the blocking probability for the call.

$$P_{bl,H} = P_{bl,H} + (1 - P_{bl,H}) P_{bl,new} \tag{9}$$

(f) Update the number of user terminals located in the spotbeam, i.e., M= M+1.
(g) Update the state probabilities to handle the handover arrival. If the handover call is still active, there should be a transition from state $i-1$ to state i for $i = 1, 2, ..., M$.

$$p_i = P_a\, p_{i-1} + (1 - P_a)\, p_i, \tag{10}$$

where P_a is the probability that the handover call is still active. Assuming exponential holding times,

$$P_a = e^{-\mu T}. \tag{11}$$

8. **Handover Departure:** If the event is a handover departure, update the state probabilities accordingly. If the call is still active, there should be a transition from state $i+1$ to state i for $i = 1, 2, ..., M-1$.

$$p_i = P_{\{a \mid s=i+1\}}\, p_{i+1} + (1 - P_{\{a \mid s=i\}})\, p_i, \tag{12}$$

where $P_{\{a \mid s=i\}}$ is the conditional probability that the call is still active given that there are i active calls in the spotbeam at this instant. $P_{\{a \mid s=i\}}$ is determined as

$$P_{\{a \mid s=i\}} = \frac{i}{M} \tag{13}$$

This is because the departures from the system result only from the call terminations. Since the call holding times of the user terminals are assumed to be identically distributed with the same mean, if there are i active calls out of M user terminals in the spotbeam, $P_{\{a \mid s=i\}}$ depends only on the number of active calls and the number of user terminals located in the spotbeam tested.

If the spotbeam tested is B_{h2}, and is located at the initial position of the origination spotbeam B_o, terminate the algorithm after evaluating the admission condition given in Step 11. Otherwise, if the handover departure call is the newly arriving call, continue with Step 10.

9. Repeat Steps 4-9.
10. Repeat Steps 3-9 for the handover spotbeams.
11. **Admission Decision:** If the condition

$$If\ \ P_{bl,CA} = \frac{E_{bl}}{E_h} \leq P_{QoS},\ \ admit\ the\ call. \qquad (14)$$

Otherwise, reject the connection request.

III. Performance Evaluation

The performance of the algorithm has been investigated using an event-driven simulation program. The speed of the spotbeams is changed by varying the maximum visibility time of the spotbeams to investigate the effect of the satellite speed over the performance. Specifically, two different values of maximum visibility time are used. For the simulation of fast spotbeams, the maximum visibility time is equal to 1 minute, while it is 2 minutes for the slow spotbeams.

The call holding times are exponentially distributed random variables with average holding time of 3 minutes. The calls arrive at the network as Poisson arrivals. Call arrival rates shown in the graphs are for an area of 8 spotbeams. Each spotbeam has 20 channels. The target blocking probability, P_{QoS}, is equal to 0.01. The performance of the GCAC algorithm is compared with that of the guard channel scheme. Specifically, for each experiment, the number of guard channels required to provide a target handover call blocking rate of 0.01 is determined.

In the first set of experiments, the users are distributed uniformly over the traffic generation area. The results for the slow spotbeams, i.e., the maximum visibility time is equal to two minutes, are shown in Figure 3. The blocking probabilities for the guard channel method with the number of guard channels equal to 1 and 2 are also shown in the Figure 3. The handover and the new call blocking probabilities are denoted as Phb and Pnb in the graphs, respectively. The handover blocking probability for the GCAC algorithm is well below the target blocking probability of 0.01. When the number of guard channels is equal to 1 in the guard channel scheme, the handover blocking probability becomes larger than 0.01 for traffic arrival rates larger than 50 calls/min. When the number of guard channels is set to 2, the target handover blocking performance can be achieved. In this case, the new call blocking probabilities for the guard channel method and the GCAC algorithm are similar. However, the GCAC algorithm can achieve almost 10 times smaller handover call blocking probabilities compared to the guard channel scheme.

The performance for the fast spotbeams as shown in Figure 4 is similar to that of slowly moving spotbeams. However, the blocking performance is slightly better for this case. The traffic arrival process to a spotbeam consists of two types of calls as the new calls and the handover calls. Since the size of the spotbeams are fixed and the users are distributed uniformly, the new call arrival rate for fast and slow spotbeams are identical. However fast moving spotbeams experience a higher handover call arrival and call departure rates. Although both types of spotbeams have similar utilization ratios, i.e., the ratio of the call arrival rate to the call departure rate, the faster system achieves lower call blocking probabilities. This is due to the fact that the spotbeam movement results in a smoothing effect in the arrival rate of the calls. At a given time interval, the fast moving spotbeam sweeps a larger area and serves the traffic in the swept area. As a result, the traffic arrival process becomes more regular and results in lower blocking probabilities.

In the second set of experiments, the performance of the GCAC algorithm is investigated using nonuniform traffic distribution in the coverage area. More specifically, five "traffic centers" are chosen randomly. For a new call arrival, a traffic center is chosen with equal probability. The exact location of the user terminal is determined using a two dimensional Gaussian distribution centered at the chosen traffic center. This traffic model is similar to the one proposed in [10] for LEO satellite network. The results for the slow spotbeams are given in Figure 5. Note that lower call arrival rates are used to achieve similar blocking performance with the uniform traffic distribution case. In addition, more guard channels should be assigned to achieve the target handover blocking probability. This constitutes a problem for the guard channel scheme since the number of guard channels should be chosen based on the expected traffic distribution over the coverage area. The accuracy of the traffic prediction affects the performance of the guard channel scheme. On the other hand, the GCAC algorithm is adaptive to the instantaneous traffic distribution, and does not require traffic prediction. Figure 5 shows the performance results for four and five guard channels. The handover call blocking performance for four guard channels is not acceptable. When the number of guard channels is equal to five, handover call blocking probability of the guard channel method and the GCAC algorithm is very similar. However, the GCAC algorithm provides lower new call blocking probability. The results for the fast moving spotbeams are similar to the that of the slow spotbeam case. However, the blocking probabilities are lower for the fast moving spotbeam case. This observation confirms the traffic smoothing effect of the spotbeam movement.

IV. Conclusions

The Geographical Connection Admission Control (GCAC) algorithm has been introduced to limit the handover call blocking probability for the spotbeam handovers in the low earth orbit (LEO) satellite networks. Upon a new call arrival, the GCAC algorithm estimates the future handover blocking performance of the users to decide whether the newly arriving call can be admitted into the network without increasing the blocking probability for the existing calls while providing the same blocking guarantee to the new user. The new call request is accepted if the handover blocking probability averaged over the contention area is less than the target blocking probability. The GCAC algorithm assumes that the exact user locations are known by the network. This is possible since the user terminals are expected to include Global Positioning System (GPS) receivers. The orbit dynamics and the spotbeam geometry are utilized to estimate

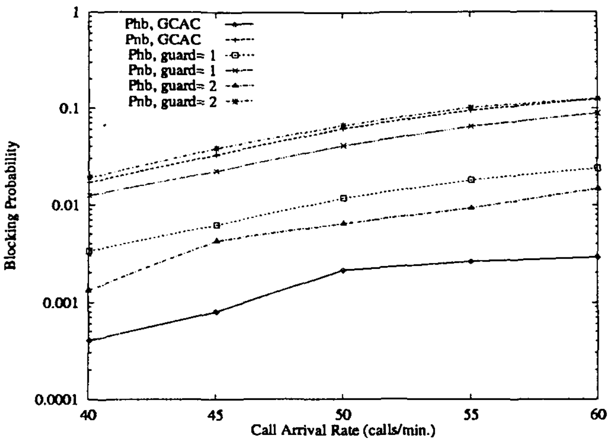

Fig. 3. The handover and new call blocking probabilities for slow spotbeams with uniform traffic distribution.

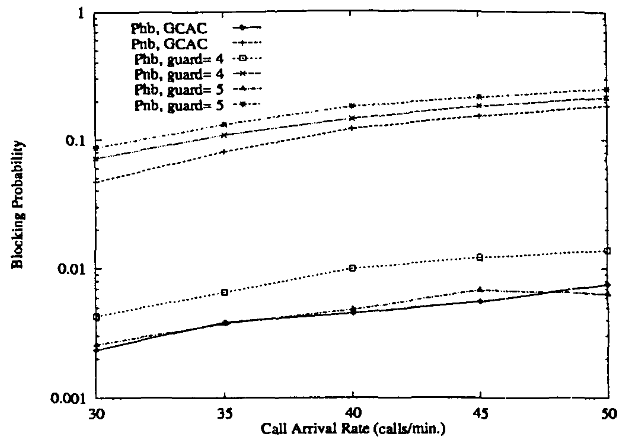

Fig. 5. The handover and new call blocking probabilities for slow spotbeams with nonuniform traffic distribution.

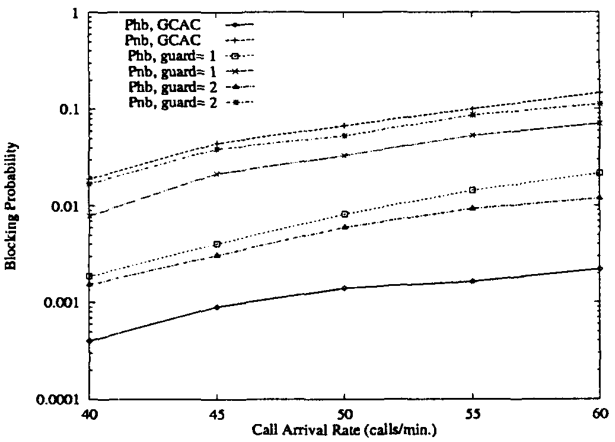

Fig. 4. The handover and new call blocking probabilities for fast spotbeams with uniform traffic distributions.

the performance metrics. The performance evaluation results show that the GCAC algorithm achieves a bounded handover blocking probability without penalizing the new calls. Moreover, the GCAC algorithm adapts to the distribution of user terminals over the coverage area and can handle nonuniform traffic distribution.

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