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A New Connection Admission Control for Spotbeam Handover in LEO Satellite Networks

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Abstract. Frequent spotbeam handovers in *low earth orbit* (LEO) satellite networks require a technique to decrease the handover blocking probabilities. A large variety of schemes have been proposed to achieve this goal in terrestrial mobile cellular networks. Most of them focus on the notion of prioritized channel allocation algorithms. However, these schemes cannot provide the connection-level *quality of service* (QoS) guarantees. Due to the scarcity of resources in LEO satellite networks, a *connection admission control* (CAC) technique becomes important to achieve this connection-level QoS for the spotbeam handovers. In this paper, a *geographical connection admission control* (GCAC) algorithm is introduced, which estimates the future handover blocking performance of a new call attempt based on the user location database, in order to decrease the handover blocking. Also, for its channel allocation scheme, an *adaptive dynamic channel allocation* (ADCA) scheme is introduced. By simulation, it is shown that the proposed GCAC with ADCA scheme guarantees the handover blocking probability to a predefined target level of QoS. Since GCAC algorithm utilizes the user location information, performance evaluation indicates that the quality of service (QoS) is also guaranteed in the non-uniform traffic pattern.

Keywords: LEO satellite networks, connection admission control, channel allocation, handover management

1. Introduction

Terrestrial mobile cellular networks provide wireless communication services with limited geographic coverage since they are economically infeasible due to rough terrain or insufficient user population. In order to provide global information access, a number of satellite systems have been proposed [11]. The satellite networks are well suited for worldwide communication services and to complement the terrestrial mobile cellular networks because they can support not only the areas with terrestrial networks but also the areas in lack of terrestrial infrastructure. Among the satellite systems, *low earth orbit* (LEO) satellite systems will make an important role in the near-future communication services, because of its less propagation delay, less power requirement in the user terminal and the satellite, and efficient spectrum utilization using smaller coverage area for each satellite than geostationary (GEO) satellite systems. Moreover, it is possible to route a connection between two satellites using inter-satellite link (ISL) without relying on terrestrial resources. However, a number of mobility problems that did not exist for GEO satellite systems should be resolved in order to have feasible implementations of the LEO satellite systems.

In LEO satellite networks, spotbeam handover[1] is the most frequently encountered network function because of the high speed of the satellites [4]. Frequent spotbeam handovers would cause more handover blockings if no resource (or channel) is available in the target spotbeam. Blocking a handover call is generally considered less desirable from user's point of view than blocking a new call [17]. The priority can be given via different treatments of new and handover calls to decrease the handover call blockings. Handover calls can experience a more favorable blocking probability than new calls by prioritizing channel allocation during call admission phase.

One noticeable prioritization scheme is *handover with queueing* (HQ) technique [4]. This scheme utilizes the overlapped area between two spotbeams where the handover takes place. When a user terminal is in an overlapped area, the handover process is initiated. If a channel is available in the new spotbeam, it is allocated to the user terminal; otherwise, the handover request is queued. When a channel becomes available, one of the calls in the queue is served. A handover call is blocked if no channel is allocated for the call in the new spotbeam when the power level received from the current spotbeam falls below the minimum power level that is required for a successful data transfer. The HQ scheme reduces the handover call blocking; however, its performance depends on the new call arrival rate and the size of the overlapped area. In the worst case, high call arrival rates or small overlapped areas would result in a high value of handover call blocking probability.

Another prioritization technique proposed is *handover with guard channel* (HG) scheme [6,7]. In this scheme, guard channels are used to ensure that some number of channels are

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[1] The definition of *spotbeam handover* will be discussed in section 2.

reserved for handover calls even when the new call arrival rate is high. In a system with guard channels, new call attempts are rejected if the number of busy channels is greater than a certain threshold. The difference between the system capacity in the number of channels and the threshold value is equal to the number of guard channels. The handover call blocking probability could be reduced by increasing the number of guard channels. Reservation of some channels for handover calls, however, increases the blocking probability for new arrivals. Hence, we need a tradeoff between the handover call blocking and new call blocking.

Along with the above techniques, various solutions have been proposed to lower the blocking probability in terrestrial mobile cellular networks [8,18]. Most of these studies focus on the notion of channel allocation algorithms. They try to maximize the channel utilization efficiency. These approaches, however, do not consider the connection-level quality of service (QoS) by explicitly controlling the handover blocking probability [13]. Due to scarcity of resources in wireless domain, *connection admission control* (CAC) policies are very important in a network's capability to guarantee connection-level quality of service (QoS).

Recently, some connection admission control (CAC) techniques in mobile cellular networks have been proposed [12, 13,19]. In [19], a simple one-dimensional model is assumed to obtain the overload probability, which is over-simplified to fit into the realistic situations. The technique proposed in [13] considers only fixed channel allocation (FCA) scheme. This scheme may lower the channel utilization efficiency. Moreover, only geographically uniform traffic patterns are investigated. In particular, the above two techniques cannot be directly applied to our problem because of the differences between the LEO satellite networks and the mobile cellular networks. A connection admission control (CAC) technique in Non-GEO satellite networks proposed in [12]. In this scheme, admission decision is based upon so-called *mobility reservation status* which provides the information about the current bandwidth requirement of all the active connections in a specific spotbeam in addition to the possible bandwidth requirements of mobile users currently connected to the neighboring spotbeams. However, this scheme has the problem of determining a threshold value and does not take the connection-level QoS issues into account.

In this paper, we propose a new connection admission control scheme called *geographical connection admission control* (GCAC) algorithm for LEO satellite networks to limit the handover blocking probability. The GCAC algorithm estimates the future handover blocking performance of a new call attempt and the existing calls based on the user location database. From the estimated handover blocking probability, the GCAC algorithm determines the acceptance or rejection of the new call. Admission control mechanisms generally rely on the underlying channel allocation scheme for the availability of a channel. For the channel allocation in the GCAC algorithm, we propose a new channel allocation scheme referred to as an *adaptive dynamic channel allocation* (ADCA) technique in this paper.

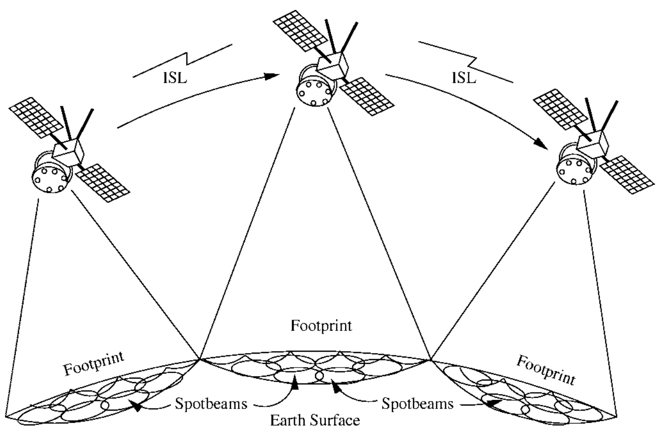


Figure 1. Spotbeams of LEO satellites.

The remaining of the paper is organized as follows. System architecture in consideration and the relationship between ADCA and GCAC algorithms are presented in section 2 along with the goal of each. In section 3, we introduce an adaptive dynamic channel allocation (ADCA). In section 4, we propose a geographical connection admission control (GCAC), which utilizes ADCA technique in section 3 as its channel allocation scheme. In section 5, we describe the mobility model and simulation assumptions in the analysis. We then compare the proposed GCAC/ADCA algorithm with other techniques described in [4,7,18]. Finally, the conclusions are drawn in section 6.

2. System architecture

In a satellite-fixed system [15], the satellites located at low earth orbits move with respect to a fixed observer on the Earth surface as shown in figure 1. The service area, i.e., *footprint* of a single satellite is a circular area on the Earth surface. The footprints of the individual satellites are covered by smaller cells or *spotbeams* to achieve frequency reuse inside the footprint. Identical frequencies can be reused in different spotbeams if the spotbeams are geographically separated to limit interference. To ensure that ongoing calls are not disrupted as a result of satellite movement, calls should be handed over to new spotbeams or satellites. The handovers between spotbeams are referred to as *spotbeam handovers* or *intra-satellite handovers* while the handovers between satellites are referred to as *inter-satellite handovers* or simply *satellite handovers*. In this paper, we focus our attention on the spotbeam handovers.

During a spotbeam handover, the communication link between the user and the satellite in the current spotbeam should be replaced with a new link in a new spotbeam. If a bandwidth is not available in the new spotbeam, the handover call will be blocked. An efficient connection admission control algorithm, therefore, has to be developed to limit the handover blocking probability. In the LEO satellite system in consideration, a connection admission control algorithm, e.g., GCAC/ADCA can be placed in the call control processor of each satellite as shown in figure 2. Calls are routed

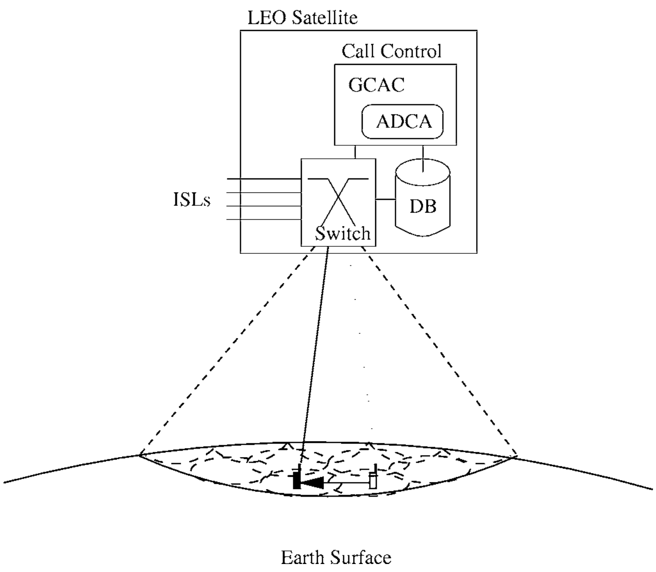


Figure 2. System architecture.

via on-board switches of the satellites. Call-specific information such as channel ID and spotbeam ID should be stored in the database (DB). Also, user mobility profiles such as user location and registry information are stored in the database. Since the DB are kept in the satellite, we do not need to exchange mobility profiles as in a distributed schemes when a user terminal is handed over to other spotbeam within a satellite. If necessary, e.g., as in inter-satellite handovers, this information is exchanged through the *inter-satellite links* (ISLs). The capacity of the DB is proportional to the number of active calls in a satellite. However, some information, such as user registry and IDs, is also mandatory for other existing channel allocation schemes. In this paper, we assume there is a sufficient storage capacity in the DB. To implement GCAC/ADCA scheme, we need only an additional entry for user location information. The user location information can be derived from either global positioning systems (GPSs) [5] or geolocation techniques [10,14,16], or hybrids of them. Technological growth in GPS system can render user terminal to be equipped with cost-effective GPS receiver with limited error. For the terminals without GPS function, various geolocation techniques need to be utilized for location estimation. Recent advances in geolocation techniques advocate their feasibility in location estimation with limited error. Hence, we assume the user location information is available in the satellite by using above techniques for our algorithm.

In general, connection admission control algorithms can seek to perform the following:[2]

1. Check the availability of bandwidth for a call request. The availability depends on a channel allocation scheme. If there is no available channel, the request is immediately rejected; otherwise, further admission test is performed.
2. Predict the next spotbeams for the call using mobility estimation technique.
3. Given the estimated call's path, estimate the blocking probability of the call request as well as the existing calls. If the estimated blocking probability is below the predefined level, the call is accepted; otherwise, it is rejected.
4. Once the call request is accepted, the channel allocation scheme has to determine which channel should be assigned to the requested call.
5. Provide smooth connection handover for handover request.

As stated in items 1 and 4, a connection admission control algorithm is tightly coupled with a channel allocation scheme. Hence, our objective is that we design an efficient channel allocation scheme and an admission control algorithm for the underlying system architecture. In section 3, we will explain the proposed ADCA scheme for items 1 and 4. In section 4, a GCAC algorithm will be proposed for items 2, 3, and 5.

3. Adaptive Dynamic Channel Allocation (ADCA)

In dynamic channel allocation (DCA) scheme[3] [4,7,18], all the channels are placed in a central pool and are assigned to call requests as needed. There is no relation between the spotbeam and channel, thus each spotbeam can select any channel that causes no interference with others. By granting more channels in overload spotbeams, DCA scheme provides an efficient channel utilization. However, DCA scheme does not exploit user mobility pattern. It leads to an inefficient channel distribution in the network, in particular under heavy traffic conditions. It is expected that we would provide more efficient channel assignment scheme by exploiting rather deterministic mobility pattern in LEO satellite networks.

Our proposed new channel allocation scheme called *adaptive dynamic channel allocation* (ADCA) is based on the dynamic channel allocation (DCA) scheme described above. It also uses the notion of *guard channel*. In the handover with guard channel (HG) technique [6,7], a fixed number of guard channels are reserved for handover calls to reduce handover blocking probability. Excessive reservation of guard channels for handover calls increases the new call blocking probabilities. Also, lack of guard channel would cause increased handover blocking probabilities. Hence, an adaptive technique which can keep track of current traffic load is essential for performance enhancement. Our new scheme dynamically adapts the number of guard channels according to the user location information. In other words, the ADCA technique finds the optimal number of guard channels for possible handovers based on the user population in the neighboring spotbeams. Accordingly, the ADCA scheme tries to prevent inappropriate use of the guard channels.

In the view of the channel allocation technique, spotbeam movement sweeping over user terminals can be considered as relative user arrivals and departures in the fixed spotbeam.

[2] However, some admission control algorithms perform only a subset of the procedure.

[3] The example and the blocking probability of the DCA scheme are given in section 4.

Hence, the ADCA algorithm simulates the user arrivals and departures in each spotbeam for a test call. When a new call arrives in a spotbeam, the ADCA scheme considers two types of possible handover events in the spotbeam occurring before the hypothetical handover departure of the new call: (1) handover arrivals from the other spotbeams; and (2) handover departures from the spotbeam where the new call is being tested for the admission. For example, as shown in figure 3, suppose a new call arrives to spotbeam # 3. Also, denote the handover residual time by τ which is the time interval between acceptance and handover departure of the new call. This time interval τ can be easily calculated according to the user location information. During this time period τ, a possible user terminal to be handed over to spotbeam # 3 would be the user B, since user A, D, and F are handed over to other spotbeams, and user C and E remain in their spotbeams assuming vertical movement of the spotbeam. Thus, the possible handover arrival is from the user B. Likewise, a possible user terminal to be handed over from spotbeam # 3 would be the user F, and accordingly possible handover departure is done by user F. In this example, we assume vertical movement of user terminal. This assumption is validated by the following statement: the satellite spotbeam moves at a very high speed (e.g., satellite velocity $v_s \approx 7{,}400$ m/s [4]) and the user terminal in a very fast vehicle moves with user velocity v_u (at most 80 m/s in current technology). Accordingly, the maximum angle between the satellite velocity vector and the user velocity vector is only about 0.6° ($= \tan^{-1} v_u/v_s$). As a result, the movement of user terminal is approximately vertical when it is seen from the LEO satellite.

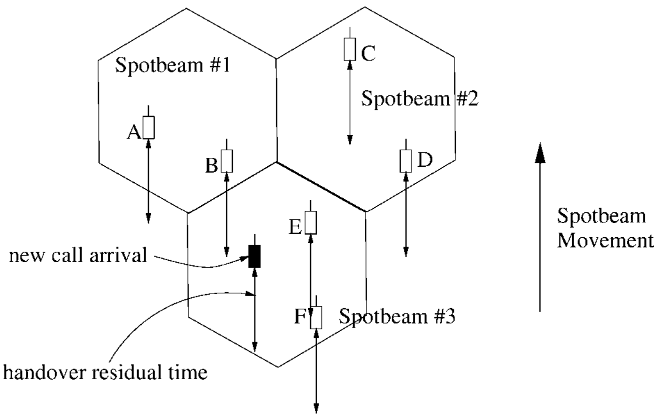


Figure 3. Illustration of ADCA scheme.

Let us denote ith handover arrival time and jth handover departure time during handover residual time τ by B_i and D_j, respectively. For example, as in figure 4, there are four handover arrival events and three handover departure events. During handover residual time τ, the number of guard channels must be maintained as the maximum number of handover events in the system (or maximum queue length), in order to ensure no handover blocking.

The number of possible handover events during τ, denoted by γ, is given by

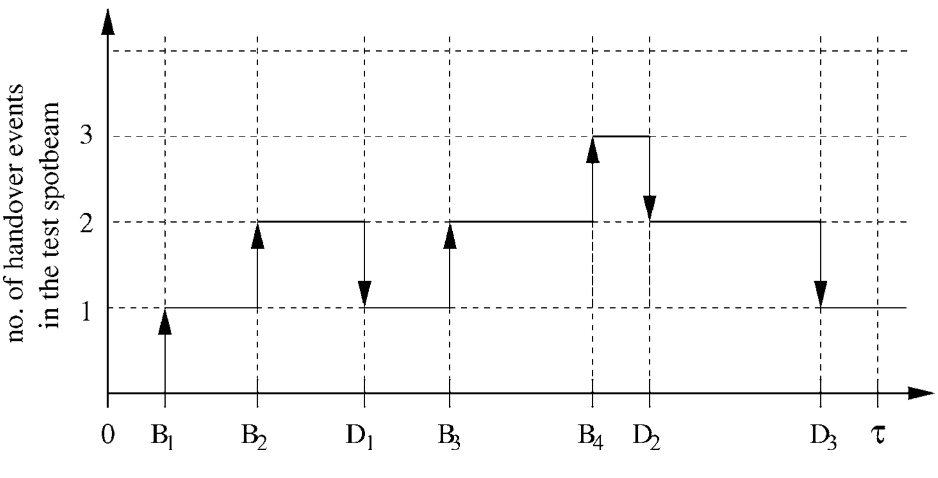
$$\gamma = \max_{\forall i} \left\{ i - \sum_{\forall j} I[D_j < B_i] \right\}, \tag{1}$$

where $I(\cdot)$ is an indicator function defined as $I(x) = 1$, if condition x is true; otherwise, $I(x) = 0$; and i and j are indices such that $B_i < \tau$ and $D_j < \tau$. As in the example of figure 4, indices that satisfy $B_i < \tau$ and $D_j < \tau$ are $i = \{1, 2, 3, 4\}$ and $j = \{1, 2, 3\}$. $\sum_{\forall j} I[D_j < B_i]$ in (1) represents the number of handover departures before ith handover arrival B_i. Hence, $i - \sum_{\forall j} I[D_j < B_i]$ will represent the number of handover events in the system right after B_i. In the example of figure 4, γ is calculated as 3 ($= \max(1, 2, 2, 3)$) which is used for the maximum number of guard channels to be reserved during τ.

However, some calls of possible users may be terminated during τ. Hence, the probability of call termination should be taken into consideration for determining the number of guard channels. Then, the *probability that a user is active during this time interval* τ can be derived by

$$\begin{aligned} P[\text{a user is active during } \tau] &= P[\tau < T_h] \\ &= e^{-\mu\tau}, \end{aligned} \tag{2}$$

where T_h denotes the *call holding time*, and it is assumed to be exponentially distributed with service rate μ.



i	$i - \sum_{\forall j} I[D_j < B_i]$		
1	1 −	0	= 1
2	2 −	0	= 2
3	3 −	1	= 2
4	4 −	1	= 3

$\gamma = max(1,2,2,3)$

Figure 4. Determination of γ.

```
ID_SPOT ⇐ current test spotbeam ID;
if (call type = new call) then {New Call Arrival}
  Calculate τ based on the new call location information;
  Calculate γ from (1);
  Calculate g̅ from (3);
  No_Ch ⇐ the number of available channels in spotbeam ID_SPOT based on DCA scheme;
  if (No_Ch > g̅) then
    Accept the call;
  else
    Reject the call;
  end if
else {Handover Call Arrival}
  ID_CH ⇐ previous channel ID;
  ID_PREV_SPOT ⇐ previous spotbeam ID;
  if ([ID_CH ∈ Set of channels used in the interfering spotbeams of spotbeam ID_SPOT] OR [ID_CH ∈ Set of channels
  in spotbeam ID_SPOT]) then
    No_Ch ⇐ the number of available channels in spotbeam ID_SPOT
    if (No_Ch > 0) then
      Accept the call;
    else
      Reject the call;
    end if
  else
    Accept the call with ID_CH;
  end if
end if
```

Figure 5. The ADCA algorithm.

Accordingly, the expected number of guard channels, $\overline{g}$, can be determined by

$$\overline{g} = \gamma \cdot \mathrm{e}^{-\mu\tau}, \tag{3}$$

where γ is given in (1).

The brief algorithm is given in figure 5. When a call arrives in a spotbeam, the spotbeam identifier is assigned to ID_{SPOT}. If the call is a new call request, handover residual time τ, the probability that a user is active during τ, and γ are calculated based on the user location information. Then, the expected number of guard channels $\overline{g}$ is obtained from (3). Note that these guard channels are used to reserve channels for possible handover calls. If the number of available channels in the spotbeam is greater than the expected number of guard channels, a new channel is assigned; otherwise, the call is rejected.

If the arriving call is a handover call request, the channel identifier that are used in the previous spotbeam is assigned to ID_{CH}, and the previous spotbeam identifier is assigned to $ID_{\mathrm{PREV\_SPOT}}$. Then, it is checked whether ID_{CH} is in the set of channels used in spotbeam ID_{SPOT} or in the interfering spotbeams of spotbeam ID_{SPOT} excluding spotbeam $ID_{\mathrm{PREV\_SPOT}}$. This is because we try to use the same channel identifier if possible, to reduce the inappropriate cost of changing channel identifier. If no spotbeams use channel ID_{CH}, the call is accepted and the same channel identifier ID_{CH} is assigned. Otherwise, other channel identifiers are checked. If there is an available channel in the interfering spotbeams of spotbeam ID_{SPOT} and spotbeam ID_{SPOT} itself, the call is accepted; otherwise, it is rejected.

As we will see in section 5.2, the ADCA scheme substantially reduces the handover blocking probability compared to other existing channel allocation schemes in [4,7,18].

4. The Geographical Connection Admission Control (GCAC)

The spotbeams of LEO satellites move along known trajectories on the Earth surface with an approximately constant speed. Moreover, the user locations can be estimated using global positioning system (GPS) receivers [5] or geolocation techniques [10,14,16] with limited location estimation error. Both the deterministic spotbeam movement and the user location information provide the handover patterns of the user terminals to the system, i.e., the future handover behavior of a user terminal can be determined. The acceptance of a new connection request increases the handover blocking probability in an area swept by the spotbeam that serves the new user. This area is referred to as a *contention area*. Let Λ be the set of user terminals in the contention area. The GCAC algorithm guarantees that the handover blocking probability is less than a target handover blocking probability, P_{QoS}. The newly arriving call is admitted to the network if the following two conditions are satisfied:

C1. The target handover call blocking probability is guaranteed for the newly arriving call.

C2. The handover blocking probability of the existing calls does not exceed the target handover blocking probability.

In our assumption, the spotbeam movement can be taken into account as relative user arrival and departure in a fixed spotbeam as in section 3. Hence, the GCAC algorithm simulates the other users' arrival and departure in each spotbeam for a test call. During the lifetime of a test call, it could be handed over to other spotbeams. If the admission decision process with the ADCA scheme decides that the above conditions C1 and C2 are not satisfied, the test call is rejected.

Our admission test is performed in two types of spotbeams: *origination spotbeam* (the spotbeam in which the test call is originated) and *transit spotbeams* (the spotbeams to which the test call is handed over). While the test call is in the origination spotbeam, other active calls can arrive and depart. This number of active calls should be taken into consideration in estimating blocking probabilities since accepting the test call could breach the target handover blocking probabilities of the other calls. Moreover, during the lifetime of the test call in the origination spotbeam, other active calls in the same spotbeam could be terminated due to call release. We use analytical expressions to estimate the number of active calls in spotbeams.

When the test call is in the transit spotbeams, it needs to estimate the number of other active calls again since this number will be changed in the new spotbeam. As in the origination spotbeam, the number of other calls should be updated in every handover event (handover arrival or handover departure) of the other calls, while the test call is in the transit spotbeams.

The *handover blocking probability*, P_b, is defined by

$$P_\mathrm{b} \triangleq \frac{E_\mathrm{b}}{E_\mathrm{h}}, \tag{4}$$

where E_b is the expected number of blocked handover arrivals, and E_h is the expected number of handover arrivals.

E_h is given by

$$\begin{aligned} E_\mathrm{h} &= E\left[\sum_{i\in\Lambda} I(\text{call } i \text{ is active at the handover instant})\right] \\ &= \sum_{i\in\Lambda} E\big[I(\text{call } i \text{ is active at the handover instant})\big] \\ &= \sum_{i\in\Lambda} p_{\mathrm{active},i}, \end{aligned} \tag{5}$$

where $I(\cdot)$ is an indicator function defined in (1), and $p_{\mathrm{active},i}$ is the probability that call i is active at the handover instant.

Likewise, E_b is given by

$$\begin{aligned} E_\mathrm{b} &= E[\text{the number of blocked handover arrivals}] \\ &= \sum_{i\in\Lambda} p_{\mathrm{b},i}\, p_{\mathrm{active},i}, \end{aligned} \tag{6}$$

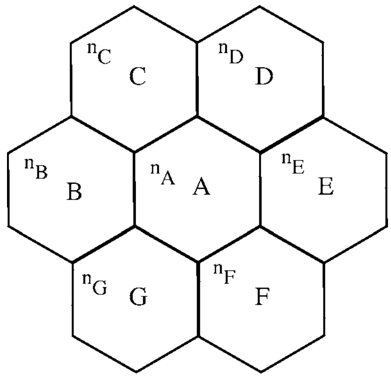


Figure 6. Spotbeam cellular architecture.

where $p_{\mathrm{b},i}$ is handover blocking probability of call i at the handover instant given that it is active at this instant.

Since the *call holding time*, T_h, is assumed to be exponentially distributed with mean $1/\mu_i$, $p_{\mathrm{active},i}$ becomes

$$\begin{aligned} p_{\mathrm{active},i} &= P[T < T_\mathrm{h}] \\ &= \mathrm{e}^{-\mu_i T}, \end{aligned} \tag{7}$$

where T is the system time.

Consider a spotbeam pattern on the ground as shown in figure 6. Define the state vector $\vec{n} \triangleq (n_A, n_B, n_C, n_D, n_E, n_F, n_G)$, where random variable n_X is the number of active users in spotbeam $X \in S$ with a set of spotbeams $S = \{A, B, C, D, E, F, G\}$. Let us assume maximum packing (MP) policy [9] is used. MP is a scheme that accepts every call to which a channel can be allocated regardless of the number of possible reassignments if reuse constraint is satisfied [9].

Suppose that a channel can be reused in every other spotbeam, i.e., the same channel can be used in spotbeams B, D, and F; or spotbeams C, E, and G in figure 6. A state vector $p(\vec{n})$ is said to be *admissible* if there exists a channel allocation to spotbeams such that no channel is used in each of two adjacent spotbeams [9]. A state vector $p(\vec{n})$ is admissible if and only if the following condition is met [9]:

$$n_A + n_B + n_C < C \tag{8}$$

for all (n_A, n_B, n_C) in figure 7, where C is the maximum number of channels when exploiting DCA technique.

This test should be carried out at the six vertices of hexagonal spotbeam A in figure 7. For example, the channel # 2 can be allocated to spotbeam A in figure 7(a) since the sum of active calls is less than $C = 4$ at each vertex of spotbeam A; however, no channels can be assigned to spotbeam A in figure 7(b) since the sum of active calls in the bottom vertex is already equal to $C = 4$.

In summary, a call can be accepted in the spotbeam A in figure 6 if

$$\begin{aligned} &(n_A + n_B + n_C < C) \cap (n_A + n_C + n_D < C) \\ &\quad \cap (n_A + n_D + n_E < C) \cap (n_A + n_E + n_F < C) \\ &\quad \cap (n_A + n_F + n_G < C) \cap (n_A + n_B + n_G < C), \end{aligned} \tag{9}$$

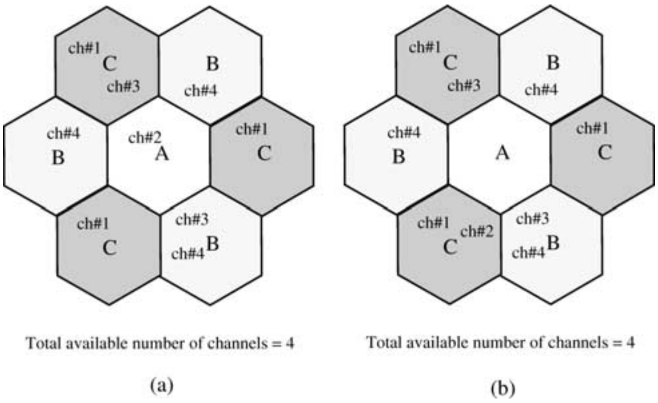


Figure 7. Example of dynamic channel allocation in spotbeams: (a) channel # 2 can be assigned in spotbeam A; (b) no channel can be assigned in spotbeam A ($C = 4$).

where again the channel reuse distance is assumed to be 2, i.e., a channel can be reused in every other spotbeam.

Then, the blocking probability of call i can be expressed as

$$\begin{aligned} p_{\mathrm{b},i} &= P\big[\{n_A+n_B+n_C \geqslant C\} \cup \{n_A+n_C+n_D \geqslant C\} \\ &\quad \cup \{n_A+n_D+n_E \geqslant C\} \cup \{n_A+n_E+n_F \geqslant C\} \\ &\quad \cup \{n_A+n_F+n_G \geqslant C\} \cup \{n_A+n_B+n_G \geqslant C\}\big] \\ &= 1 - \sum_{n_A=0}^{C-1} \sum_{n_B=0}^{C-n_A-1} \sum_{n_C=0}^{C-n_A-n_B-1} \sum_{n_D=0}^{C-n_A-n_C-1} \\ &\quad \times \sum_{n_E=0}^{C-n_A-n_D-1} \sum_{n_F=0}^{C-n_A-n_E-1} \sum_{n_G=0}^{C-n_A-n_F-n_B-1} p(\vec{n}). \end{aligned} \quad (10)$$

To derive a closed-form solution of the stationary distribution $p(\vec{n})$, we deal with this problem using Jackson network [2], as shown in figure 8. In this way, we map our system to Jackson network analysis. First, suppose that there are K queues (or spotbeams), and each of K queueing systems has m_i servers (channels) where $i \in S$. In our case, $K = 7$. Also, it must satisfy the condition $\sum_{i \in S} m_i \leqslant C$. Second, the external arrival process to the ith queue is Poisson with rate λ_i since we assume that the new call arrival process is Poisson. For each user, the service times at each queue are mutually independent and independent of the arrival process at the queue. Let $h_{i,j}$ denote the probability that a user departs queue i and then joins queue j where $i, j \in S$. Thus, an actual arrival rate to the queue i is $\gamma_i = \lambda_i + \sum_{j \in S} \gamma_j h_{j,i}$. Furthermore, we assume $\sum_{i \in S} h_{j,i} < 1$, where $h_{j,0} = 1 - \sum_{i \in S} h_{j,i}$ is the probability that a user leaves the system after served at the queue j. In other words, the mobile user will leave the system with probability one. Finally, the system is stable, i.e., $\rho_i = m_i \gamma_i / \mu_i < 1\ \forall i \in S$, since the queueing network is a loss system. In real system, the values λ_i, γ_i, and $h_{j,i}$ are measured over time in each of the spotbeams.

Based on the above mappings to Jackson network and Jackson's theorem, the equilibrium distribution of the state vector $p(\vec{n})$ can be expressed as product form [2]:

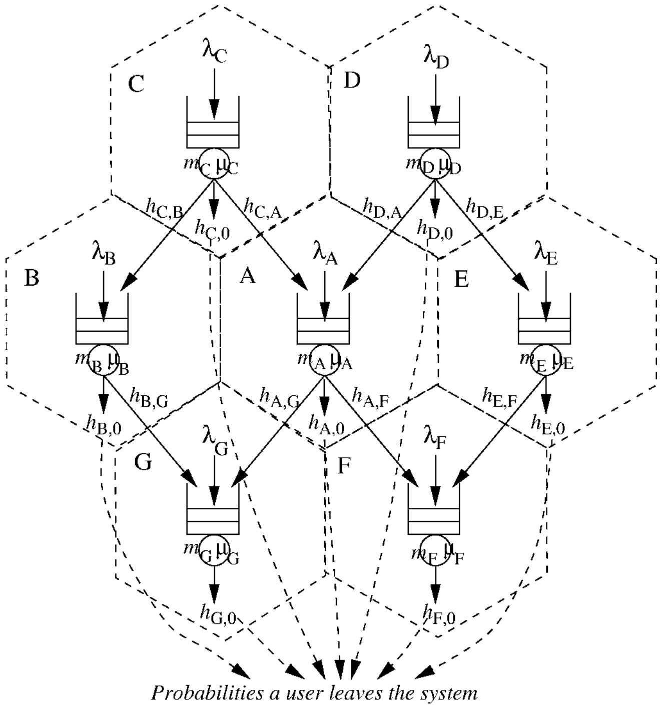


Figure 8. Queueing network model for spotbeams.

$$p(\vec{n}) = \prod_{X \in S} p(n_X), \quad (11)$$

where $p(n_X)$ is the stationary distribution of the number of active calls in the spotbeam $X \in S$. Whenever the test call is handed over to next spotbeam, it is initialized by

$$p(n_X = i) = \begin{cases} 1.0, & i = M_X, \\ 0.0, & i \neq M_X, \end{cases} \quad (12)$$

where M_X is the number of user terminals located in the spotbeam X, and M_X is incremented by one for handover arrival and decremented by one for handover departure.

The GCAC algorithm operates similar to an event-driven simulation. Upon a new call arrival, the spotbeams hypothetically move along their respective trajectories. During the spotbeam movement, handover arrival and departure events occur. System statistics are updated for every handover events. At event epochs, analytical expressions are used to estimate the system state and the handover blocking probability. The time interval between successive events is referred to as the handover event gap, Δ. Between the gap, 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 call terminations. This is followed by the update of the system state according to the handover event.

If the handover call is still active upon a handover arrival, there should be a transition from state $(i-1)$ to i for

$i = 1, 2, \ldots, M_X + 1$. Therefore, when a handover arrives, stationary distribution $p(n_X = i)$ can be updated as follows:

$$p(n_X = i) = p_{\text{active},i} \cdot p(n_X = i - 1) + (1 - p_{\text{active},i}) \cdot p(n_X = i) \quad \text{for } i = 1, 2, \ldots, M_X + 1, \tag{13}$$

where $p_{\text{active},i}$ is computed in (7), and $p(n_X = i)$ is initialized as in (12).

If the handover call is still active upon a handover departure, only the transition from state $(i + 1)$ to i is possible for $i = 0, 1, \ldots, (M_X - 1)$. Hence, when a handover departs, $p(n_X = i)$ can be determined by

$$p(n_X = i) = \frac{i+1}{M_X} p(n_X = i + 1) + \left(1 - \frac{i}{M_X}\right) p(n_X = i) \quad \text{for } i = 0, 1, \ldots, M_X - 1. \tag{14}$$

Departures from the system result only from the call terminations. Since the call holding time of the users are assumed to be identically distributed, the conditional probability that the call is still active given that there are i active calls in the spotbeam only depends on the number of active calls and the number of users located in the spotbeam tested. Since only call terminations could occur between handover events (handover arrivals or departures), i.e., only downward transitions are possible in the time interval $(T,\ T + \Delta)$, the stationary distribution $p(n_X = i)$ can be updated as follows:

$$p(n_X = i) = \sum_{j=i}^{M_X} P_{ji}(\Delta) p(n_X = j) \quad \text{for } i = 0, 1, \ldots, M_X, \tag{15}$$

where

$$P_{ji}(\Delta) = \binom{j}{j-i} \left(e^{-\mu\Delta}\right)^i \left(1 - e^{-\mu\Delta}\right)^{j-i}, \tag{16}$$

which is the probability that out of j active calls, $(j - i)$ calls terminated in a time interval of length Δ, and i active calls remained.

If the condition

$$P_b = \frac{E_b}{E_h} \leqslant P_{QoS} \tag{17}$$

is satisfied, the call is admitted to the network. Otherwise, it will be rejected. The brief algorithm is given in figure 9.

5. Performance evaluation

5.1. Assumptions

The mobility model in the simulation is assumed to be as follows:

- The cellular layout is regular hexagonal as shown in figure 10.[4] We assume the radius R of the circle inscribed in a hexagonal spotbeam is 212.5 km [4]. Accordingly, the length R' of a spotbeam side is 245.4 km (since $R' = 2R/\sqrt{3}$).
- Mobile users cross the cellular network with a constant relative velocity orthogonal to the side of the spotbeams. We assume ground track speed V_{trk} of a satellite to be 26,600 km/h [4]. From the radius of the spotbeam circle and ground track speed, the maximum connection time in a spotbeam will be approximately 0.55 min.
- When a handover occurs, the destination spotbeam is the neighboring spotbeam in the direction of the relative satellite-user motion.
- The call holding time T_h is exponentially distributed with average holding time of 3 min.
- The call arrival process is Poisson in all spotbeams.
- A cluster consists of 19 different spotbeams (from spotbeams A to S) for channel allocation purpose as shown in figure 10. Different channels have to be assigned in each of the 19 spotbeams.
- The same channel can be assigned in different spotbeams at the same time provided that these spotbeams are sufficiently separated in space (reuse distance). In other words, the same channel can be assigned in spotbeams indexed by i where $i \in \{A, B, \ldots, S\}$ in figure 10. Frequency reuse distance is assumed to be as $D = 2\sqrt{19}R$, which can be easily obtained by the distance of spotbeams A to A as in figure 10 ($D = \sqrt{(4R)^2 + (6R)^2 - 2(4R)(6R)\cos 2\pi/3}$).

For performance comparison, we developed a simulation tool containing following spotbeam handover schemes:

Scheme 1. FCA [7].
Scheme 2. DCA [4].
Scheme 3. DCA2 [4].
Scheme 4. Handover with queueing [4] using DCA2 scheme (DCA2-HQ).
Scheme 5. Handover with one guard channel (HG) [6,7].
Scheme 6. Handover with two guard channels (HG) [6,7].

In the FCA technique [7], a set of channels is permanently assigned to each spotbeam. The same set of channels is reused in different spotbeams at the same time if these spotbeams are sufficiently separated (i.e., separated at least reuse distance D away). The basic FCA technique implies that a call attempt at a spotbeam can only be served by any available channel belonging to the set of channels assigned to that spotbeam. If no channel is available, the call is blocked and forced to be terminated. The DCA scheme [4] permits an efficient spectrum utilization because each channel may be used in any spotbeam of the network, provided that the constraint on the reuse distance D is respected. No fixed relationships exist between the channel and the spotbeams. In DCA2 algorithm [4], channel

[4] Detailed description of the figure will be given later in this subsection.

if (A channel is available in the origination spotbeam using ADCA technique) **then**
  $p_{\mathrm{b},i} \Leftarrow 0, \forall i \in \Lambda$;
  $E_\mathrm{h} \Leftarrow 0$;
  $E_\mathrm{b} \Leftarrow 0$;
  while (The test call reaches through three consecutive spotbeams) **do**
    $T \Leftarrow 0$;
    $A \Leftarrow$ identifier of the spotbeam where the test call resides;
    Assign the neighboring spotbeam identifiers to $B, \ldots, G$ as in figure 4;
    Initialize distribution as (12), $\forall X \in \{A, B, \ldots, G\}$;
    while (The test call remains in spotbeam A) **do**
      Determine the next handover event based on the user locations;
      $A \Leftarrow$ identifier of the spotbeam where the handover event arrives;
      Update system state as (15);
      $T \Leftarrow T + \Delta$;
      if (Handover event = handover departure) **then** {Handover Departure}
        Calculate $p_{\mathrm{active},i}$ as (7);
        Update system state as (14);
        $M_X \Leftarrow M_X - 1$;
        Calculate $p(\vec{n})$ as (11);
      else {Handover Arrival}
        Calculate $p_{\mathrm{active},i}$ as (7);
        Update system state as (13);
        $M_X \Leftarrow M_X + 1$;
        Calculate $p(\vec{n})$ as (11);
        Calculate E_h and E_b as (5) and (6), respectively;
      end if
    end while
  end while
  $P_\mathrm{b} \Leftarrow E_\mathrm{b}/E_\mathrm{h}$;
  if ($P_b < P_{\mathrm{QoS}}$) **then**
    Accept the call;
  else
    Reject the call;
  end if
else
  Reject the call;
end if

Figure 9. The GCAC algorithm.

allocation is performed on demand on the basis of the evaluation of a cost function defined for each available channel (the cost function and detailed description of the algorithm can be found in [4]). DCA2-HQ [4] is an enhanced version of DCA2 scheme by incorporating handover queueing(HQ) technique. This scheme substantially reduces the handover blocking probability. In HG [7], guard channels are used to ensure some number of channels are reserved for handover calls. Particularly, in this scheme, we use FCA technique as a channel allocation strategy.

For DCA schemes, total C channels can be allocated to 19 spotbeams (from spotbeams A to S in figure 10). For FCA schemes, $C/19$ channels can be assigned to each spotbeam. In other words, the maximum number of channels that can be used within a spotbeam is C and $C/19$ for DCA and FCA schemes, respectively, provided that no limit on the number of terminals has been placed. In particular, to avoid an edge effect,[5] results have been collected only from the 61[6] central spotbeams in figure 10.

For the performance evaluation of the proposed algorithm, discrete-event simulation technique is utilized. With this technique, the simulation clock is initialized to zero, and the times of occurrence of future events are determined. Then, the simulation clock is advanced to the time of the most imminent event, the state of the system is updated, and future event times are determined. These series of clock advances are continued until the prespecified ending condition reaches. The user location perceived by the spotbeam is continuously moving; however, in our simulation, all state periods of inactivity are skipped over by jumping the simulation clock from event

[5] Edge spotbeams may not have sufficient interfering spotbeams for them. Hence, the edge spotbeams can have more channels to be assigned.

[6] To make it clear, note that 61 spotbeams are for measurement, and 19 spotbeams are for a cluster.

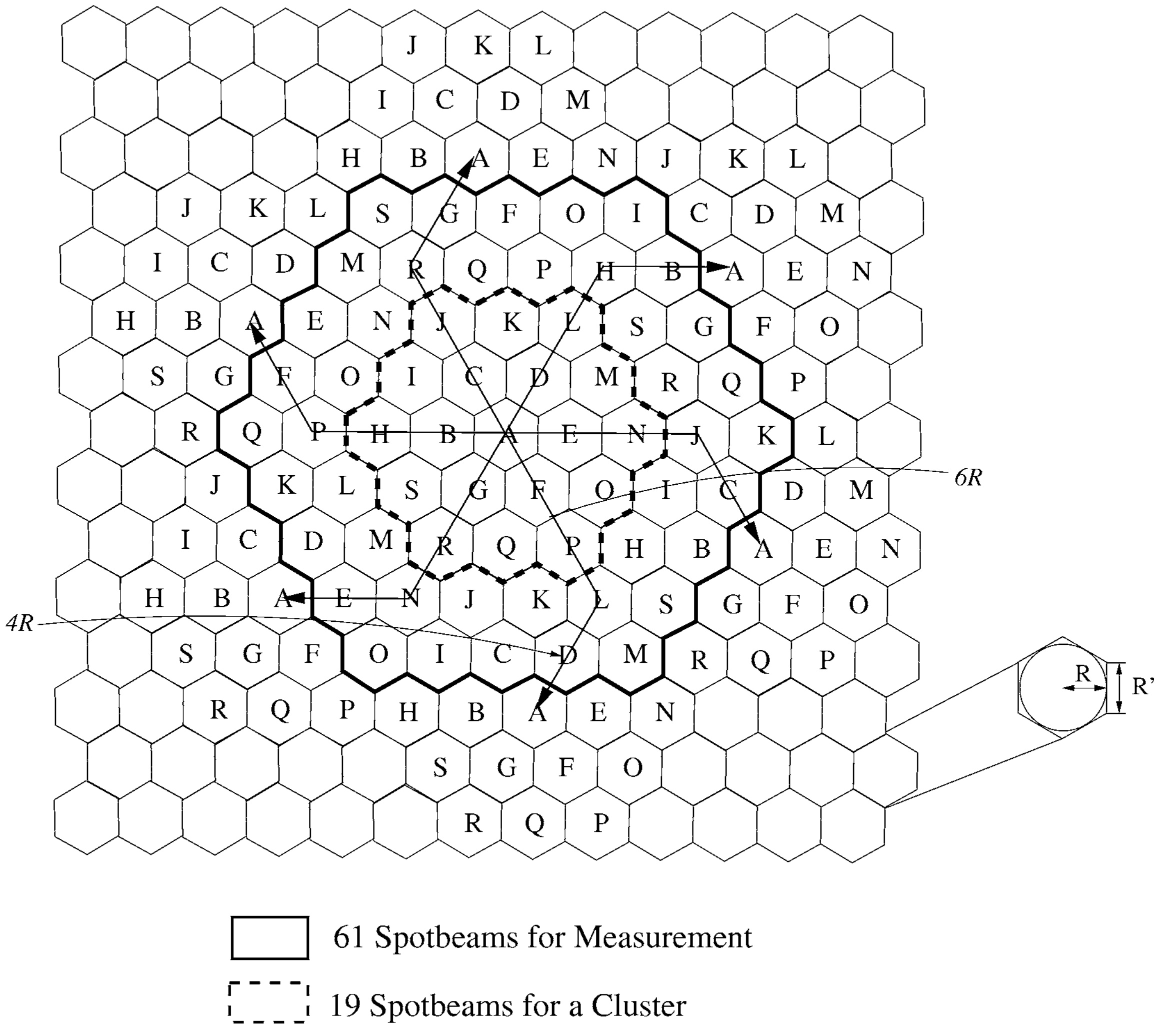


Figure 10. Cellular architecture in simulation.

time to event time. When a new call is accepted to a spotbeam, its call holding time is set according to exponential distribution. This time is stored in the event list and used for a future call release event. Depending upon the user location, the handover time of the new call is determined, which is used for a next handover event.

5.2. *Performance evaluation of ADCA and GCAC*

The performance can be investigated using both uniform and non-uniform traffic distribution in the coverage area. In case of uniform distribution, every spotbeam generates the calls with the same arrival rate. Here, we consider the uniform traffic generation, and the performance under non-uniform traffic distribution will be evaluated in the next subsection. Also, we take into account very restricted number of channels. Since a channel cost in satellite networks is very expensive compared to other terrestrial cellular networks, the number of resources in satellite networks should be taken differently from in the terrestrial cellular networks of urban areas. Results are obtained in a very limited number of available resources considering worst case scenarios. The new call and handover call blocking probabilities are shown in figures 11 and 12, respectively, when the number of channels in 19 spotbeams is 190 ($C = 190$).

In terms of new call blocking probability, the DCA2 (scheme 3) and DCA2-HQ (scheme 4) techniques perform better than the others as shown in figure 11. However, these schemes show unacceptable handover blocking probabilities in heavy load region as in figure 12. In the handover with guard channel (HG) schemes (schemes 5 and 6), the new call blocking probability is very high since the schemes are based on FCA, and the number of guard channels is overestimated in both cases of one and two guard channels. The FCA technique (scheme 1) shows also very poor characteristics because the channels are not well utilized. Note that the FCA scheme in here does not exploit handover queueing technique. Our schemes ADCA and GCAC/ADCA show higher new call blocking probabilities. However, both schemes achieve acceptable level of new call blocking probability (less than 10^{-2}).

On the other hand, as illustrated in figure 12, our ADCA scheme and GCAC/ADCA scheme cause substantial decreases of handover blocking probabilities over the other tech-

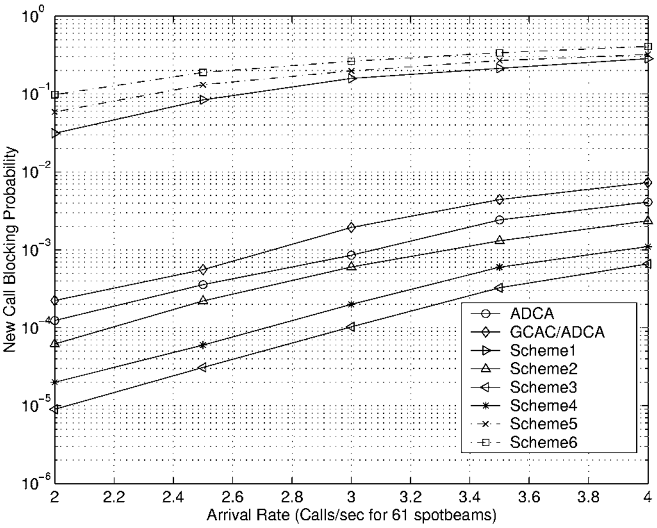


Figure 11. New call blocking probabilities ($C = 190$).

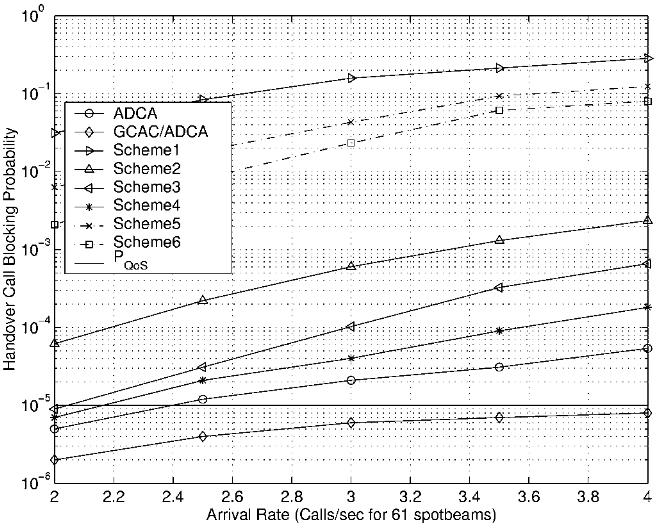


Figure 12. The handover call blocking probabilities ($C = 190$).

niques at the expense of increased new call blocking probabilities. In this case, our target handover blocking probability P_{QoS} is assumed to be 10^{-5}. With respect to this target level, however, ADCA scheme still cannot meet this requirement. By adding the GCAC scheme to the ADCA scheme, we guarantee the target level. Throughout the simulation experiments, the GCAC algorithm guarantees the target handover blocking probability ($P_{\text{QoS}} = 10^{-5}$).

For our GCAC/ADCA scheme, we varied the number of channels and investigated their effects on the new call and handover call blocking probabilities as shown in figure 13. In this case, the input traffic load is 4 calls/s for 61 spotbeams. Also, uniform user distribution is assumed. As expected, our scheme guarantees the target level of handover blocking probability ($P_{\text{QoS}} = 10^{-5}$), and the new and handover call blocking probabilities decrease as the number of channels increases. However, the figure shows that the slope of the handover blocking probability is less sensitive than that of the new call blocking probability. Our GCAC/ADCA scheme

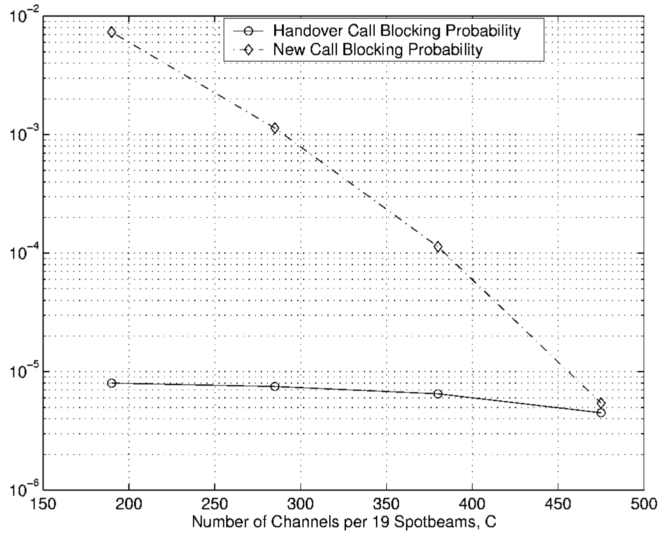


Figure 13. The effect of the number channels on the new call and handover blocking probabilities in GCAC/ADCA scheme (4 calls/s for 61 spotbeams).

provides substantial decrease of the new call blocking probability as the number of channels increases while it keeps the handover blocking probability below the target level. This indicates the GCAC/ADCA provides good performance on both new and handover call blocking in sufficient number of channels.

5.3. *Effect of nonuniform user distribution*

In most of previous studies, uniform distribution for user location has been assumed. However, in reality, the distribution of user terminals over the Earth surface cannot be uniform, e.g., spotbeams of LEO satellites may cover a number of crowded cities as well as lightly populated areas such as ocean and mountains. In case of the non-uniform distribution, the traffic generation is time-varying, i.e., a certain spotbeam does not generate any traffic at some time period but it could be overloaded sometime later.

For the non-uniform traffic pattern, we generate 35% of new calls in a center spotbeam,[7] and then we generate the remaining 30, 20, 10, and 5% of new calls in the spotbeams of the first, second, third, and fourth *tier*,[8] respectively. In this experiment, the number of channels for 19 spotbeams C is assumed to be 190 ($C = 190$).

We compare our scheme GCAC/ADCA with DCA2-HQ technique (scheme 4) which showed a better performance than others except GCAC/ADCA in the previous experiments. As shown in figures 14 and 15, we can capture the effect of non-uniform traffic, i.e., the overall blocking probabilities increase in non-uniform traffic distribution. Also, GCAC/ADCA provides lower handover blocking probabilities independent of the traffic patterns. In addition, we can

[7] In figure 10, it implies a center spotbeam A within 61 spotbeams for measurement.

[8] The tier is the group of spotbeams surrounding the center spotbeam A. In figure 10, the first tier is composed of spotbeams B to G, the second tier consists of spotbeams H to S, etc.

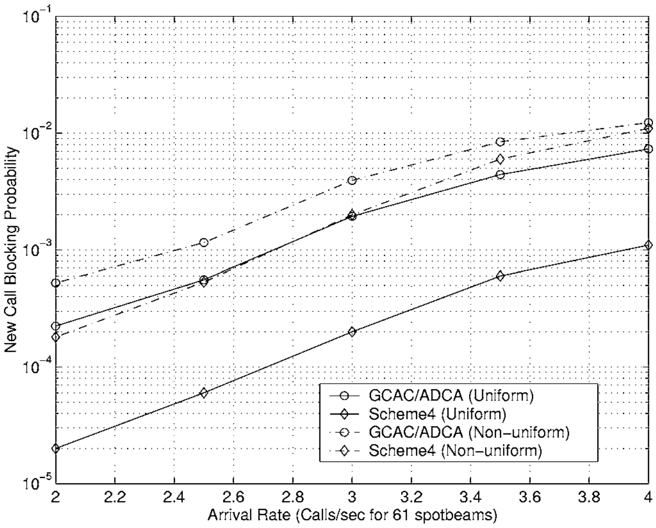


Figure 14. New call blocking probabilities (traffic pattern comparison).

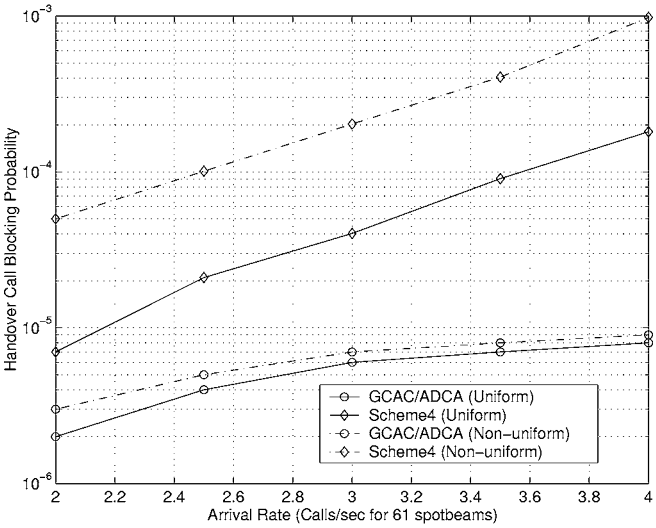


Figure 15. The handover call blocking probabilities (traffic pattern comparison).

observe that the difference of blocking probabilities between two traffic patterns become less in the GCAC/ADCA scheme than in DCA2-HQ scheme, i.e., the GCAC/ADCA algorithm is less affected by the traffic pattern than the DCA2-HQ technique. This shows that GCAC/ADCA technique very well estimates the user population distribution.

6. Conclusions

A geographical connection admission control (GCAC) algorithm has been proposed in order to limit handover blocking probability in low earth orbit (LEO) satellite networks. The GCAC algorithm estimates the future handover blocking performance of the new call attempts based on the user location database. This technique could be very important in quality of service (QoS) provisioning satellite networks in the future. As a channel allocation scheme in the GCAC, we also have introduced an adaptive dynamic channel allocation (ADCA) scheme. We have shown that the proposed GCAC/ADCA scheme limits the handover blocking probabilities to a predefined target level (QoS). The GCAC/ADCA algorithm can also be well suited for non-uniform traffic pattern since it utilizes the user location information to estimate the handover blocking probabilities.

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