Handover Queuing Strategies with Dynamic and Fixed Channel Allocation Techniques in Low Earth Orbit Mobile Satellite Systems

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Abstract— This paper deals with the performance evaluation of various resource management strategies that are suitable for low earth orbit–mobile satellite systems (LEO-MSS's). A user mobility model has been proposed and its statistical parameters have been derived. Both fixed channel allocation (FCA) and dynamic channel allocation (DCA) techniques have been considered. Moreover, in order to reduce the handover failure probability, we have assumed that interbeam handover requests which do not immediately obtain service can be queued. In particular, two different queuing disciplines have been compared: a) the first input first output (FIFO) scheme and b) a new technique called last useful instant (LUI) which is based on the knowledge of the maximum time within which the handover procedure must be accomplished. Implementation aspects for the LUI technique in a LEO-MSS have been discussed also in comparison with the measurement-based priority scheme (MBPS), previously proposed in the literature on this subject. The efficiency of the LUI queuing scheme as regards the FIFO technique has been investigated by simulations for both DCA and FCA techniques. An analytical approach has been also presented in order to allow the performance evaluation of the FCA scheme with different handover queuing disciplines.

Index Terms—Dynamic channel allocation, satellite communications.

I. INTRODUCTION

THE POTENTIALITY of the future cellular market is incredibly large, since half of the world's population lives more than two hours away from a telephone [1]. At present, R&D efforts are addressed toward the achievement of mobile services on a global basis. The integration of mobile satellite systems (MSS's) with terrestrial cellular networks [2]–[4] will pave the way for future third-generation mobile communication systems, named *International Mobile Telecommunications after the year 2000* (IMT-2000) [5].

Several satellite orbital constellations have been proposed for MSS's. An interesting solution is given by low earth orbit (LEO) satellites, since they permit relaxation of the constraints on the link budget, allow the use of low-power handheld mobile terminals, and ensure the earth coverage with smaller cells, so achieving a higher traffic capacity [6]–[9].

LEO satellites are not stationary with respect to a fixed point on the earth: the satellite ground-track speed V_{trk} is far greater than the earth rotation speed and the user speed [7]. Two different approaches are possible for the cellular coverage with LEO-MSS's: 1) cells (=spot-beam footprints on the earth) are fixed on the earth and satellite antenna spot-beams are steered so as to point to the same area during all the time the satellite is above the horizon (e.g., TELEDESIC system [9]) and 2) cells move on the earth according to the satellite motion (e.g., IRIDIUM system [7], [8]). This paper deals with the second solution that requires specific procedures to manage the cell change for an active call. Moreover, we consider only a voice traffic. Each time a call arrives at a cell x, it must be served by an available channel in x; call attempts that do not immediately find free resources are blocked and lost [blocked calls cleared (BCC)].

The main problem is that the spectrum assigned to LEO-MSS's [10] is reduced with respect to the expected market diffusion of these services. Therefore, optimized radio resource management strategies have to be investigated for LEO-MSS's. First, we have considered a fixed channel allocation (FCA) technique and we have developed an analytical approach to derive the system performance in this case. Moreover, we have considered dynamic channel allocation (DCA) techniques [11]–[15], because they are more efficient resource management strategies that can provide MSS's with a high capacity. Owing to analytical difficulties, the DCA performance has been derived only by simulations.

When an active mobile subscriber (MS) goes out from a cell and enters an adjacent one, a new channel must be automatically assigned to it in order to have a seamless conversation. This procedure is called *handover*; it involves the rerouting of a call between two adjacent beams that may belong to either the same satellite or two adjacent satellites of the MSS's. If no channel is available in the destination cell, the handover is unsuccessful and the call is dropped.

The selection of a suitable policy for managing handover requests is a central issue in defining resource management strategies. From the user standpoint, the interruption of a conversation is more undesirable than the blocking of a newly arriving call. In LEO-MSS's, interbeam handover requests are extremely frequent during call lifetime (one could expect that a call experiences a handover request every 1 min or even less) and at each beam change the call may be dropped due to an unsuccessful handover. Hence, LEO-MSS's require specific techniques that prioritize the service of handover requests
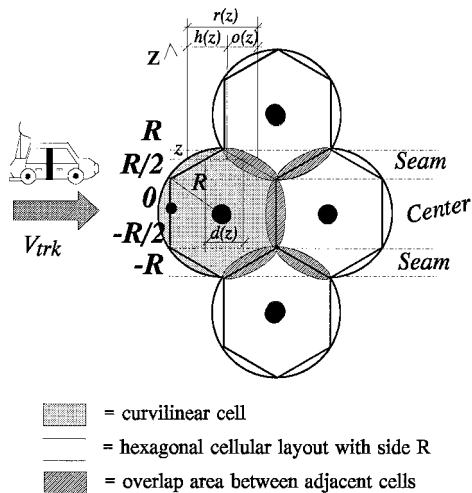
Fig. 1.   The geometry of the cellular network with a hexagonal layout.

with respect to the service of new call attempts in order to reduce as much as possible the call dropping probability. Many policies have been recently proposed to privilege handovers at the expenses of new call arrivals in terrestrial microcellular systems [12], [16]–[21]. The aim of this paper is to present a suitable mobility model and to compare the performance of different handover queuing strategies in LEO-MSS's.

This paper has been organized as follows: Section II deals with some preliminary assumptions. Section III presents a suitable mobility model that has been analyzed in Section IV. Both FCA and DCA techniques are described in Section V. Section VI presents different handover queuing disciplines. An analytical study for the FCA technique with handover queuing is presented in Section VII. Finally, Section VIII deals with simulation results for both DCA and FCA.

II. BASIC ASSUMPTIONS

This paper utilizes IRIDIUM system data [8] as an example for numerical evaluations, but the results obtained here are generally valid for all LEO-MSS's based on the moving cells approach described in Section I. In particular, the IRIDIUM system is based on 66 satellites over six near polar circular orbits at about 780 km of altitude (consequently, $V_{trk} = 26\,600$ km/h).

Let us assume that spot-beam footprints on the earth have a regular shape due to beam-forming. Moreover, we consider that each multispot-beam antenna from a satellite irradiates on the earth a regular honeycomb cellular network, where R is the cell side (Fig. 1). Therefore, the centers of adjacent cells are separated by a distance equal to $\sqrt{3}R$. In the IRIDIUM case, we have assumed R equal to 212.5 km [14].

In this paper, we do not refer to a particular multiple access technique (TDMA, CDMA, FDMA); a channel is a resource shared among users according to allocation rules.

New calls are assumed to arrive at the cells according to a Poisson process independent of cell to cell, and the unencumbered call duration is considered exponentially distributed with average value T_m.
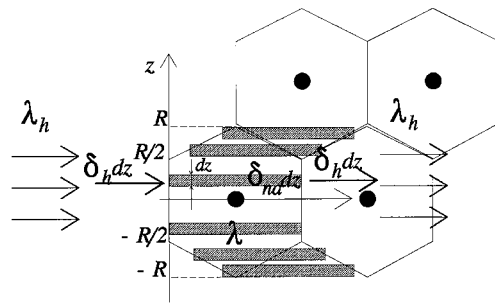

Fig. 2.   The flow conservation for handover requests that enter and handover requests that go out from a cell.

According to the BCC policy for the voice traffic, the following quality of service (QoS) parameters are used to evaluate the performance of resource management strategies:

- the blocking probability of new call attempts P_{b1};
- the handover failure probability P_{b2};
- the call dropping probability P_{drop};
- the unsuccessful call probability P_{ns}, because the call is initially blocked or it is dropped due to the failure of a subsequent handover request.

The QoS parameters directly experienced by MS's are P_{b1} and P_{drop}. ITU-T in the recommendation E.771 [22] has specified that P_{drop} and P_{b1} should not exceed $5 \cdot 10^{-4}$ and 10^{-2}, respectively. These requirements, given for land mobile cellular systems, have been adopted here for LEO-MSS's, even if they may seem too severe, by considering future high-quality mobile communication systems.

Finally, only mobile-to-fixed user calls and fixed-to-mobile user calls have been taken into account, because mobile-to-mobile user calls are expected to be a little percentage of the whole traffic (maximum 5%).

III. THE LEO MOBILITY MODEL

In order to study the handover generation process toward a cell and evaluate the impact of handover strategies on the performance of resource management techniques, it is necessary to model the user mobility. Then, the following aspects have to be considered: 1) the propagation conditions in the satellite radio channel; 2) the user motion with respect to cells; and 3) the geometry of the cells and their disposition, that is the topology of the network. In order to reduce the analytical complexity of the model, a widely used approach [14], [17], [23] is to neglect propagation aspects; therefore, this study takes only into consideration the user motion and the network topology.

We name *source cell* the cell where the MS call starts and *transit cell* any subsequent cell reached by the MS with the call in progress. Referring to *a given cell* x, subscript $i = 1$ will be used for the statistical parameters related to calls started in cell x, whereas subscript $i = 2$ will be used for the parameters related to handed-over calls to cell x. We consider hexagonal regular cells with side R (see Figs. 1 and 2); this assumption will allow us to obtain a simple analytical characterization of user mobility.

The relative satellite-MS motion can be approximated by only the satellite ground-track speed (i.e., vector V_{trk}), due to the high value of V_{trk} with respect to the other motion component speeds. This consideration also entails that the relative motion has a fixed orientation with respect to the cellular layout irradiated on the earth by satellites. Let the track of the relative motion be disposed, as shown in Fig. 1.

Moreover, MS's (and the calls they generate) are considered uniformly distributed[1] over the simulation area [13]–[15]. Therefore, a newly arriving call can occur with equal probability in every point of the satellite cellular network.

According to the above assumptions, we have the following.

- When a new call arrival occurs, any cell of the system has the same probability to be the source cell of this arrival.
- Once the source cell of a call is defined, a random offset $z \in [-R, R]$ is associated to this call.[2] The probability density function (pdf) of z, $f(z)$, is obtained by taking into account that active MS's are uniformly generated within a cell and they move in straight lines with fixed z values. A new call in its source cell belongs to a horizontal elementary strip with side $d(z)$ and height dz (see Fig. 2) according to a probability given by the ratio between the strip area $[=d(z)\,dz]$ and the cell area $(=3\sqrt{3}R^2/2)$. Then, $f(z)$ is given by

$$f(z) = \frac{d(z)}{3\dfrac{\sqrt{3}}{2}R^2} \tag{1}$$

where $d(z)$ is

$$d(z) = \begin{cases} \sqrt{3}R, & \text{if } |z| \le \dfrac{R}{2} \\ 2\sqrt{3}(R - |z|), & \text{if } R \ge |z| > \dfrac{R}{2}. \end{cases} \tag{2}$$

- Once the offset z of the MS is chosen in the source cell, the distance covered in this cell by the MS from the call arrival instant is uniformly distributed between zero and $d(z)$.

According to the uniform spatial generation for new call attempts, the offset z of an MS in a transit cell is uniformly distributed. It follows that the pdf of the offset z according to which an MS crosses the source cell $(i = 1)$ or a transit cell $(i = 2)$, $f_i(z)$, can be obtained as

$$f_i(z) = \begin{cases} f(z), & \text{if } i = 1 \\ \dfrac{\{u[z + R] - u[z - R]\}}{2R}, & \text{if } i = 2 \end{cases} \tag{3}$$

where:

$$u(x) \triangleq \begin{cases} 1, & x \ge 0 \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

[1] Even if LEO-MSS's will be characterized by time-varying traffic conditions, we use the hypothesis of uniform traffic, because it allows generic performance evaluations which do not depend on specific traffic conditions (see also the next section). The interested reader may find more details on this subject in [3].

[2] If we refer to a satellite polar constellation (e.g., IRIDIUM) on the basis of previous assumptions on the disposition of the cellular layout with respect to the ground-track speed, we obtain that the coordinate z in Figs. 1 and 2, here called *offset,* is related to the MS longitude.

We can summarize the proposed LEO mobility model as follows.

1) MS's cross the cellular network with a relative velocity (i.e., vector V_{trk}), disposed as shown in Fig. 1 with respect to the cellular layout.
2) When a handover occurs, the destination cell will be the neighboring cell in the direction of the relative satellite-MS motion.
3) MS's cross the cellular network with an offset uniformly distributed all over the network.
4) From the call arrival in a cell, where z is the offset of the related MS according to the reference shown in Fig. 1, the related MS travels a distance in this cell which is

- uniformly distributed between zero and $d(z)$ if the cell is the source cell of the call;
- deterministically equal to $d(z)$ if the cell is a transit cell of the call.

In order to characterize the user (relative) mobility in LEO-MSS's, we introduce the dimensionless parameter α as

$$\alpha \triangleq \frac{\sqrt{3}R}{V_{trk}T_m} \tag{5}$$

where T_m is the average call duration.

Parameters R and V_{trk} depend on the satellite constellation altitude; moreover, R also depends on the half power beam width (HPBW) of the satellite antenna spot-beams. Typical α values are 0.20–0.60 for LEO-MSS's, if $T_m = 3$ min. The smaller α is, the more frequent the handover requests are during call lifetime: i.e., the mobility increases [see (25) and (26) in the next section]. In particular, in the IRIDIUM mobility case under examination ($R = 212.5$ km, $V_{trk} = 26\,600$ km/h) α is about equal to 0.27, if $T_m = 3$ min.

With respect to the previously proposed LEO mobility model [13]–[15], this model takes into account that an MS with a call in progress may cross the cellular layout not only along the central region of cells (see Fig. 1), but also through the seam of the cellular network. In such a case, we expect that the number of interbeam handovers during call lifetime is significantly increased. This entails a more realistic evaluation of the impact of user mobility on the performance of channel allocation techniques for LEO-MSS's. Finally, it is worth noting that the mobility model proposed in this paper is valid for whatever type of MS's, since V_{trk} is far greater than the speed of every kind of MS, it does not matter if it is pedestrian, vehicular, or flying in a plane.

IV. ANALYSIS OF THE LEO MOBILITY MODEL

Let us refer to a given cell x. We denote by t_{mc2} the time spent by an MS to cross cell x from border to border (i.e., the mobile sojourn time in a cell), and by t_{mc1} the time spent in cell x by an MS from the new call arrival instant. The distributions of variables t_{mci} can be easily derived as

$$\text{Prob}\{t_{mci} < t\} = \int_{-R}^{R} \text{Prob}\{t_{mci} < t \,|\, z\} f_i(z)\, dz \tag{6}$$

where

$$\text{Prob}\{t_{mci} < t \,|\, z\}$$
$$= \begin{cases} \dfrac{tV_{trk}}{d(z)}\left\{u(t) - u\left[t - \dfrac{d(z)}{V_{trk}}\right]\right\} \\ \qquad + u\left[t - \dfrac{d(z)}{V_{trk}}\right], & \text{if } i = 1; \\ u\left[t - \dfrac{d(z)}{V_{trk}}\right], & \text{if } i = 2. \end{cases} \quad (7)$$

The pdf of variables t_{mci} are obtained by taking the derivative of (6) with respect to variable t. Through some algebraic manipulations we have

$$\text{pdf}_{t_{mc1}}(t) = \frac{2}{3}\left\{2 - \frac{t}{\alpha T_m}\right\}\frac{\{u(t) - u(t - \alpha T_m)\}}{\alpha T_m} \quad (8)$$

and

$$\text{pdf}_{t_{mc2}}(t) = \frac{\{u(t) - u(t - \alpha T_m)\}}{2\alpha T_m} + \frac{1}{2}\delta(t - \alpha T_m) \quad (9)$$

where $\delta(t)$ is the Dirac delta function.

The expressions for the distributions of the random variables t_{mc1} and t_{mc2} are not independent of each other, because t_{mc1} can be considered as a residual time in the interval t_{mc2} starting from an arrival instant within t_{mc2} (*excess life theorem* [19], [24], [25]). Hence, $\text{pdf}_{t_{mc1}}(t)$ and $\text{pdf}_{t_{mc2}}(t)$, respectively, given by (8) and (9), can be related as

$$\text{pdf}_{t_{mc1}}(t) = \frac{1 - \displaystyle\int_{\tau=0}^{t}\text{pdf}_{t_{mc2}}(\tau)\,d\tau}{E[t_{mc2}]}. \quad (10)$$

Since the unencumbered call duration t_d is exponentially distributed, the same distribution is valid for the residual call lifetime after a handover request (*memoryless property*). Therefore, we still denote by t_d the residual call lifetime.

A handover procedure is started for an MS with a call in progress in cell x whenever $t_d > t_{mci}$, with $i = 1$ if cell x is the source cell for the call, or $i = 2$ if cell x is a transit cell for the call. The probabilities of these events, P_{Hi}, $i = 1, 2$, can be obtained as follows:

$$\begin{aligned} P_{Hi} &= \text{Prob}\{t_d > t_{mci}\} \\ &= \int_0^{+\infty}\text{Prob}\{t_d > t \,|\, t_{mci} = t\}\,\text{pdf}_{t_{mci}}(t)\,dt \\ &= \int_0^{+\infty}e^{-(t/T_m)}\,\text{pdf}_{t_{mci}}(t)\,dt \\ &= \mathcal{L}(\text{pdf}_{t_{mci}}(t))|_{s=1/T_m} \qquad i = 1, 2 \end{aligned} \quad (11)$$

where $\mathcal{L}(g(t))$ denotes the Laplace transform of the function $g(t)$ [24].

By substituting (8) and (9) into (11) and by performing some algebraic manipulations, we obtain the handover probabilities P_{H1} and P_{H2}

$$P_{H1}(\alpha) = \frac{2}{3}\left\{P_{h1}(\alpha) + \frac{1 - P_{h1}(\alpha)}{\alpha}\right\}$$

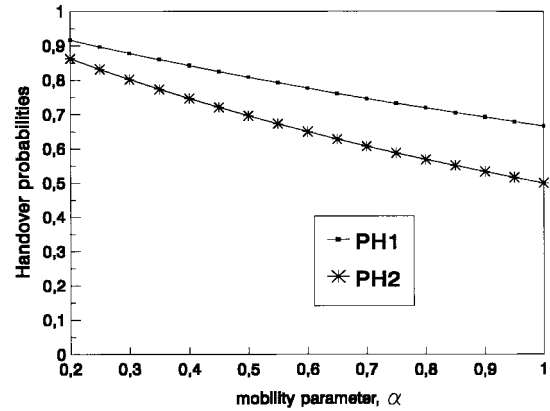$$P_{H2}(\alpha) = \frac{P_{h1}(\alpha) + P_{h2}(\alpha)}{2} \quad (12)$$

Fig. 3. Handover probabilities P_{H1} and P_{H2} as a function of the mobility parameter α.

where

$$P_{h1}(y) \triangleq \frac{1 - e^{-y}}{y}, \qquad P_{h2}(y) \triangleq e^{-v}. \quad (13)$$

Note that $P_{hi}(y)$ in (13), $i = 1, 2$, represents the handover probability for a call (with mean duration T_m) from a cell, where the related MS crosses a distance (from the call arrival instant) which is:

- uniformly distributed between zero and q for $i = 1$;
- fixed and equal to q for $i = 2$

where $y = q/[V_{trk}\,T_m]$. More details are given in [14].

Handover probabilities P_{H1} and P_{H2} only depend on the mobility parameter α. Fig. 3 shows the behaviors of P_{H1} and P_{H2} as a function of α. It is evident that as α approaches zero (∞), P_{H1} and P_{H2} approach one (zero), i.e., the mobility increases (decreases).

The channel holding time for calls in cell x can be derived as [17]

$$t_{Hi} = \min[t_d, t_{mci}], \qquad i = 1, 2. \quad (14)$$

The statistical distribution of variable t_{Hi}, $i = 1, 2$, can be derived by means of the approach outlined in [17]. For the sake of brevity, we give below only the final result for the expected value of t_{Hi} [24]

$$E[t_{Hi}] = T_m(1 - P_{Hi}), \qquad i = 1, 2. \quad (15)$$

Equation (15) shows that, due to mobility, the average channel holding time in a cell (both source cell and transit cell) is reduced with respect to T_m.

We would like to point out that in this paper the performance evaluation of different handover strategies has been limited to the uniform traffic case, because it allows us to focus on the more generic aspects of the system rather than obtaining results for very specific traffic profiles. However, our study can be extended to the case of nonuniform traffic on the condition that a suitable traffic distribution be provided. The same authors have presented in [25] a traffic model based on a market forecast for future IMT-2000 [see Fig. 11(a)]. With reference to that traffic model, we have shown in Fig. 11(b), Section VIII, a performance comparison in terms of P_{ns} between FCA and DCA both employing the queuing of handover

requests (see Sections V and VI). As expected, the advantages of the DCA technique are enhanced in this case. A further investigation on this point is beyond the scope of this paper.

According to the uniform traffic assumption, we denote by λ the average arrival rate of new call attempts in a generic cell of the system. The handover arrival process examined here is related to calls managed by the MSS which need to be passed from cell to cell: i.e., interbeam handovers. The new handover arrival process in a cell depends on both the motion of MS's as regards the cells, the shape and size of cells, and MS's distribution on the territory. Since all cells have the same shape and size by means of beamforming, all MS's have the same motion conditions as regards the cells (due to the high value of the satellite ground-track speed). Moreover, the MS distribution on the territory is uniform and the average handover arrival rate toward a cell, λ_h, is the same for all the cells (see Fig. 2). We obtain a relationship between λ_h and λ by application of the flow balance condition among outgoing handover requests and incoming handover requests in a given area [14]. In particular, we consider flow conservation equations on horizontal strips with elementary height dz and length $\sqrt{3}R$ that are disposed on the cellular network at offsets z, from $z = -R$ to $z = R$ (see Fig. 2). The elementary arrival rates in a generic strip are $\delta_{na}(z)\,dz$ and $\delta_h(z)\,dz$ for new call attempts and handover requests, respectively. The sum of the elementary rates $\delta_h(z)\,dz$ for the strips from $z = -R$ to $z = R$ gives the average arrival rate of handover requests toward a cell

$$\int_{-R}^{R} \delta_h(z)\,dz = \lambda_h. \tag{16}$$

The sum of the areas of the elementary strips from $z = -R$ to $z = R$ is equal to 4/3 the area of a cell. Due to the uniform spatial generation of new call arrivals, δ_{na} is independent of z. Hence, we have

$$\int_{-R}^{R} \delta_{na}\,dz = \frac{4}{3}\lambda \implies \delta_{na} = \frac{2}{3R}\lambda. \tag{17}$$

In the following analysis, we will distinguish the case $|z| \leq R/2$ from the case $R \geq |z| > R/2$.

1) Case $|z| \leq R/2$: The flow balance condition is analogous to that shown in [14], but instead of parameters λ and λ_h, we have to consider terms $\delta_{na}\,dz$ and $\delta_h(z)\,dz$ which are related to a generic elementary strip at the offset z

$$\delta_{na}\,dz(1-P_{b1})P_{h1}(\alpha)+\delta_h(z)\,dz(1-P_{b2})P_{h2}(\alpha) = \delta_h(z)\,dz. \tag{18}$$

Let λ_{hc} denote the average handover rate for the central part of a cell defined as

$$\lambda_{hc} = \int_{-R/2}^{R/2} \delta_h(z)\,dz. \tag{19}$$

Through integration of (18) from $z = -R/2$ to $z = R/2$ and by using (17) and (19), we have

$$\frac{\lambda_{hc}}{\lambda} = \frac{2}{3}\frac{(1-P_{b1})P_{h1}(\alpha)}{1 - (1-P_{b2})P_{h2}(\alpha)}. \tag{20}$$

2) Case $R \geq |z| > R/2$: The cell border divides an elementary strip at the offset z into two segments with length $d(z)$ and $\sqrt{3}R - d(z)$, respectively. Let us denote

$$\alpha_1(z) = \frac{d(z)}{V_{trk}T_m}, \qquad \alpha_2(z) = \frac{\sqrt{3}-d(z)}{V_{trk}T_m}. \tag{21}$$

Therefore, we have $\alpha_1(z) + \alpha_2(z) = \alpha$.

Owing to the uniform spatial generation of new calls, a new call arrival (in the strip) occurs in the first segment with a probability $d(z)/(\sqrt{3}R) = \alpha_1/\alpha$ [see (21)] and in the second segment with a probability $[\sqrt{3}R - d(z)]/(\sqrt{3}R) = \alpha_2/\alpha$ [see (21)]. Consequently, a new call arrival originated in this strip gives rise to a handover request with a probability $(1 - P_{b1})\,[(\alpha_1/\alpha)P_{h1}(\alpha_1)P_{h2}(\alpha_2)(1 - P_{b2}) + (\alpha_2/\alpha)P_{h1}(\alpha_2)]$. Whereas a call handed-over toward the strip requires a new handover with a probability equal to $(1 - P_{b2})P_{h2}(\alpha_1)(1 - P_{b2})P_{h2}(\alpha_2) = (1 - P_{b2})^2 P_{h2}(\alpha)$. Hence, we have the following flow balance equation:

$$\delta_{na}\,dz(1-P_{b1})\left[\frac{\alpha_1}{\alpha}P_{h1}(\alpha_1)P_{h2}(\alpha_2)(1-P_{b2})+\frac{\alpha_2}{\alpha}P_{h1}(\alpha_2)\right]$$
$$+\delta_h(z)\,dz(1-P_{b2})^2 P_{h2}(\alpha) = \delta_h(z)\,dz. \tag{22}$$

Let us integrate both sides of (22) on the seam of the cellular network, i.e., from $z = -R$ to $z = -R/2$ and from $z = R/2$ to $z = R$. For the symmetry of the problem, this is equivalent to integrating both sides of (22) multiplied by two, from $z = R/2$ to $z = R$. Moreover, we divide the result by λ and we obtain λ_h/λ as

$$\frac{\lambda_h}{\lambda} = \frac{\lambda_{hc}}{\lambda} + \frac{2}{3}(1 - P_{b1})$$
$$\cdot\frac{1 - P_{h1}(\alpha) + (1 - P_{b2})(P_{h1}(\alpha) - P_{h2}(\alpha))}{\alpha - \alpha(1 - P_{b2})^2 P_{h2}(\alpha)} \tag{23}$$

where, from (16) and (19), we have

$$2\int_{R/2}^{R} \delta_h(z)\,dz = \lambda_h - \lambda_{hc}. \tag{24}$$

Note that in deriving (20) and (23) we have not made any assumption on the behavior $\delta_h(z)$ as a function of z. Finally, by substituting (20) into (23), we have

$$\frac{\lambda_h}{\lambda} = \frac{2}{3}(1 - P_{b1})\left\{\frac{P_{h1}(\alpha)}{1 - (1 - P_{b2})P_{h2}(\alpha)}\right.$$
$$\left. + \frac{1 - P_{h1}(\alpha) + (1 - P_{b2})(P_{h1}(\alpha) - P_{h2}(\alpha))}{\alpha - \alpha(1 - P_{b2})^2 P_{h2}(\alpha)}\right\}. \tag{25}$$

According to [14] and [24], the average number of handover requests per call attempt arrived at the system, n_h, can be related to λ_h/λ as

$$n_h = \frac{\lambda_h}{\lambda}\frac{\text{handover requests}}{\text{call attempt}}. \tag{26}$$

Parameter n_h is a useful measure of the degree of mobility of the environment. If $P_{b1} = P_{b2} = 0$, the value of n_h given by (25) is maximum and equal to $4/(3\alpha)$; in particular, in the IRIDIUM mobility case ($R = 212.5$ km, $V_{trk} = 26\,600$ km/h), on average, 4.9 handovers are required per call with $T_m = 3$ min. It is important to point out that the proposed

mobility model makes a difference to the results with respect to a simplified model where all MS's cross a fixed distance in a cell [14], [15]. Let us consider a cellular system equivalent to that obtained with hexagonal cells in Fig. 1, but where we eliminate the seam by using rectangular cells: these cells have the following sizes: $\sqrt{3}R \times 1.5R$ and have the same area of hexagonal cells. Each MS crosses in a cell a distance $\sqrt{3}R$ from border to border. In this case we use the study carried out in [14] and [15]: if $P_{b1} = P_{b2} = 0$, $n_h = 1/\alpha$ (=3.6 handovers/call with IRIDIUM data and $T_m = 3$ min). Hence, this simplified model underestimates the handover rate and, then, call blocking probabilities.

Among all arrived calls, we have both blocked calls (with probability P_{b1}) and calls admitted into the network (with probability $1 - P_{b1}$). The average number of handover requests per call admitted in the network, n'_h, can be related to the average number of handover per call attempt n_h by taking into account that the quantity $1 - P_{b1}$ is the average number of accepted calls per call arrived. Therefore, if we multiply n'_h by $1 - P_{b1}$, we obtain n_h. Hence, the following relationship is valid:

$$n'_h = \frac{n_h}{1 - P_{b1}} \quad \frac{\text{handover requests}}{\text{call accepted}}. \quad (27)$$

It is easy to verify that if an accepted call originates, on average, n'_h handover requests, and if at each request the call may be dropped with probability P_{b2}, the overall call dropping probability is [14]

$$P_{\text{drop}} = n'_h P_{b2}. \quad (28)$$

Finally, probability P_{ns} can be derived as [14]

$$P_{ns} = P_{b1} + (1 - P_{b1})P_{\text{drop}}. \quad (29)$$

V. CHANNEL ALLOCATION TECHNIQUES

In this paper, we assume that the channel allocation techniques have to fulfill the following constraint: two different cells on the earth may reuse the same channel provided that they are at a suitable distance, called *reuse distance D* which allows tolerable levels for the cochannel interference. As stated before, we consider FCA and DCA techniques. A short description of both strategies is given below.

A. Fixed Channel Allocation

With the FCA technique, a set of channels is permanently assigned to each cell, according to the allowed reuse distance D. A call can only be served by an available channel (if any) belonging to the set of the cell. If an arriving call does not find any free nominal channel in its cell, the call is blocked and lost.

For uniform traffic conditions, the full set of M channels is divided into equal groups each composed by S channels [26]

$$S = \frac{M}{K}, \quad \text{where} \quad K = \frac{D^2}{3R^2}. \quad (30)$$

In (30), parameter K is the number of cells that form the FCA cluster [26]. The spatial repetition of this cluster assures the territory coverage as in a mosaic.

The use of FCA in a situation with nonuniform traffic requires a complex network planning in order to assign more capacity in the cells where a higher traffic is expected. In the LEO contest under consideration, such planning is meaningless because the traffic offered to a given cell is unpredictable due to the fast satellite motion with respect to the earth. This is the reason why a more suitable solution for LEO-MSS's is given by the DCA approach, as described below.

B. Dynamic Channel Allocation

A DCA strategy allows that any system channel can be temporarily assigned to any cell, provided that the constraint on the reuse distance D is fulfilled. Let x be the cell of the arrival, $I(x)$ the set of interfering cells with x (i.e., those cells that lie at a distance less than D from x), and $\Lambda(x)$ the set of available channels in x [i.e., those channels that are not used either in x or in the cells belonging to $I(x)$].

The DCA technique considered here has been introduced in [14]; it selects the channel i^* to be allocated in the cell of the call arrival x according to the following minimum cost criterion:

$$C_x(i^*) = \min_{i \in \Lambda(x)} \{C_x(i)\}. \quad (31)$$

The cost function $C_x(i)$ used in (31) has been defined as follows:

$$C_x(i) \triangleq q_x(i) + \sum_{k \in I(x)} \{C_x(k, i)\} \quad \forall i \in \Lambda(x) \quad (32)$$

where the cost contribution for channel $i \in \Lambda(x)$, due to the interfering cell $k \in I(x)$, $C_x(k, i)$, is given by

$$C_x(k, i) = v_k(i) + 2(1 - q_k(i)) \quad \forall k \in I(x) \quad (33)$$

and

$$v_k(i) = \begin{cases} 1, & \text{if } i \in \Lambda(k) \\ 0, & \text{otherwise,} \end{cases}$$

$$q_k(i) = \begin{cases} 0, & \text{if } i \in F_D(k) \\ 1, & \text{otherwise.} \end{cases} \quad (34)$$

This DCA technique selects (whenever possible) channels belonging to $F_D(x)$, i.e., the set of channels that are assigned to x by FCA. Otherwise, the DCA strategy selects in $\Lambda(x)$ the channel that becomes locked in the minimum number of interfering cells of x. Finally, if $\Lambda(x) = \emptyset$, the call is blocked.

In order to enhance the DCA performance, whenever a call termination occurs in a cell x (due to either the physical end of a call or a handover), a channel is released in x according to a deallocation criterion with a cost-function complementary to that used in the allocation phase [14]. The deallocation cost-function selects (to be freed in x) the channel j^* that becomes available in the greatest number of interfering cells and, possibly, a channel that does not belong to the FCA pattern of x. If channel j^* differs from channel j' on which the call is actually ended, the call in progress in x on channel j^* must be rearranged on channel j'. Further details on this DCA technique are given in [14].

VI. THE QUEUING OF HANDOVER REQUESTS

Let us consider an MS with a call in progress that leaves cell x and enters an adjacent cell y; there is an area where this MS can receive a signal with an acceptable power level from both cells; this is the so-called *overlap area*. The time the MS spends to cross the overlap area $t_{w\,\max}$ can be used to queue the related handover request if no channel is free in cell y. An interbeam handover strategy based on the queuing of handover requests (QH) is essential to meet the ITU-T requirements for P_{drop}, as shown in Section II.

In the following, FCA NPS (DCA NPS) will denote the fixed (dynamic) channel allocation technique with no prioritization scheme (NPS) for handover requests; whereas FCA-QH (DCA-QH) will denote the fixed (dynamic) channel allocation technique with the queuing of handover requests.

A. Overlap Areas Model

In general, $t_{w\,\max}$ is a random variable that depends on both the degree of overlap between adjacent beams (i.e., antenna characteristics and satellites orbital configuration), the signal strength, propagation conditions (i.e., the mobile environment: rural, urban, etc.), and the MS motion direction as regards the cellular layout.

Let us assume that, due to beam-forming, spot-beam footprints are disposed on the earth according to a hexagonal regular layout (side R) and they have a circular coverage with radius R'. In the literature, the possible values for the ratio R'/R range from 1 to 1.5 [27]. Obviously, the greater this ratio is, the larger the overlap area is and then the better the queuing technique performance is. In this paper, the minimum possible extension of the overlap area has been considered: $R = R'$ (see Fig. 1).

Once the position of the MS at the call arrival instant is defined, an offset z is assigned to this MS in the source cell. Due to both the regular cellular layout and the mobility assumptions, the distance $o(z)$ covered by the MS in the overlap area remains the same for any handover request, it does not matter if it originates from a source or a transit cell. For an MS crossing the overlap area at the offset z, parameter $t_{w\,\max}$ is obtained as

$$t_{w\,\max} = \frac{o(z)}{V_{trk}}. \tag{35}$$

Note that, according to the assumptions made, the randomness of $t_{w\,\max}$ only depends on the offset z of the related MS that crosses the cellular network.

We assume circular spot-beam footprints on the earth with radius R that give overlap areas as shown in Fig. 1. Due to the *deterministic nature* of the relative MS-satellite motion in LEO-MSS's, we consider that calls generated in the overlap area are automatically addressed to the destination spot-beam in order to avoid these calls generating handover requests soon after being served. Hence, the term *cell* denotes a region where all new calls are managed by the same spot-beam. The study of overlap areas entails a curvilinear cell shape (see the shaded region in Fig. 1), instead of the hexagonal one, previously assumed in the mobility model. Let $r(z)$ denote the distance crossed by an MS in a curvilinear cell at the offset z

$$r(z) = 2\sqrt{R^2 - z^2}. \tag{36}$$

The maximum distance covered in a curvilinear cell before giving rise to a handover request $h(z)$ is

$$h(z) = r(z) - o(z) \tag{37}$$

where $o(z)$ is given by

$$o(z) = \begin{cases} 2\sqrt{R^2 - z^2} - \sqrt{3}R, & \text{if } |z| \leq \dfrac{R}{2} \\[2ex] \sqrt{R^2 - z^2} - \dfrac{\sqrt{3}}{2}R \\[1ex] \quad + \sqrt{R^2 - \left(|z| - \dfrac{3}{2}R\right)^2}, & \text{if } R \geq |z| > \dfrac{R}{2}. \end{cases} \tag{38}$$

Note that the area of this curvilinear cell is equivalent to that of the hexagonal cell with side R (i.e., $3\sqrt{3}R^2/2$). Then, according to the hypothesis of uniform traffic load, λ represents the mean arrival rate of new call attempts for both curvilinear and hexagonal cells. On the basis of the new cell shape,[3] we can recompute the pdf of the offset z of a new call attempt in its source cell $f^*(z)$ by using the same approach shown in Section III to derive the pdf $f(z)$ for hexagonal cells

$$f^*(z) = \frac{h(z)}{3\dfrac{\sqrt{3}}{2}R^2}. \tag{39}$$

Of course, the pdf of the offset of an active MS in a transit cell is still uniform, as for hexagonal cells. In Fig. 4 the distributions $f(z)$ and $f^*(z)$ are compared; we may note that $f^*(z)$ is not significantly different from $f(z)$. Therefore, the analytical results, which have been derived in the previous sections on the basis of a hexagonal cell shape, can be also extended, with a good approximation, to the case of curvilinear cells.[4] We use $f^*(z)$ to derive the average value of the maximum queuing time $E[t_{w\,\max}]$ as

$$\begin{aligned} E[t_{w\,\max}] &= \frac{E[o(z)]}{V_{trk}} \\ &= \frac{1}{V_{trk}} \int_{z=-R}^{z=R} o(z) f^*(z)\, dz \\ &= \alpha T_m \beta \end{aligned} \tag{40}$$

where β is given by

$$\beta = \frac{4}{9}\left(\frac{\sqrt{3}}{3}\pi - \frac{3}{2}\right) \approx 0.1394. \tag{41}$$

Parameter β is dimensionless and it only depends on the geometric assumptions made to model the user mobility and the overlap areas.

In particular, we have $E[t_{w\,\max}] \approx 7$ s from (40) for the IRIDIUM mobility case.

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[3] We can rewrite the points 1–4 of the mobility model in Section III for curvilinear cells, by substituting $h(z)$ to $d(z)$.

[4] Please refer to [28] for the analytical computation of all the parameters of the mobility model with curvilinear cells (i.e., P_{Hi}, n_h, P_{drop}, and λ_h/λ) and to verify the goodness of the approximation made. Note that the use of hexagonal cells allows an easier analytical formulation of the mobility model.
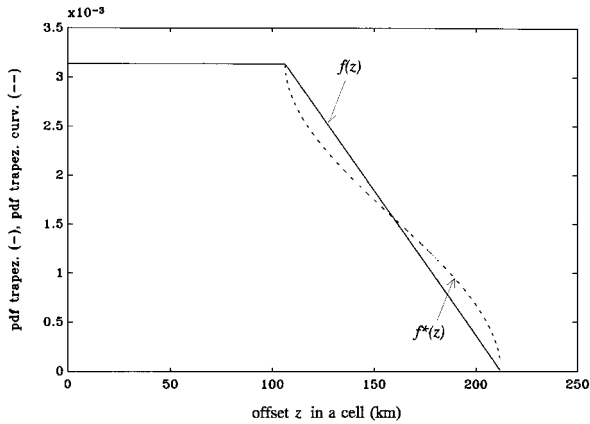
Fig. 4.   Comparison between the probability density functions $f(z)$ and $f^*(z)$ in the IRIDIUM case.

B. The Management of Handovers with the Queuing of Initially Blocked Requests

Let us assume that a handover procedure is started as soon as an active MS goes into the overlap area between cell x and cell y. Let $\Lambda(y)$ denote the set of free channels in the generic cell y. The interbeam handover request is served according to the following *make-before-break* arrangement.

1) If $\Lambda(y) \neq \emptyset$, the handover is immediately performed: a new channel is assigned to the MS in cell y and the old channel is released in cell x.

2) If $\Lambda(y) = \emptyset$, the handover request is queued waiting for an available channel in cell y (see Section VI-C). In the meantime, the call is served by cell x. A handover request leaves the queue owing to one of the three following reasons [29].

- *The handover procedure is successful:* the handover is performed before the call is over and its maximum queuing time has expired.

- *The handover request declines:* the call ends before the corresponding handover request is accomplished and its maximum queuing time has expired.

- *The handover procedure fails and the associated call is dropped:* the handover has not been performed within $t_{w\,\max}$ and the call is not ended before its maximum queuing time has expired.

C. Queuing Disciplines

Different schemes can be applied depending on the way handover requests are ordered in the queue. The most common queuing discipline is the first input first output (FIFO) scheme [14], [15], [17], where handover requests are queued according to their arrival instants. A more complex policy is the measurement-based priority scheme (MBPS) [16], [30]. MBPS uses a nonpreemptive dynamic priority policy, where the handover priorities are defined by the power levels that the satellite receives for the related calls from their current spot-beam (we assume a network controlled handover technique, where the handover procedure is managed by the satellite [19]). The target is to serve first the calls with a more degraded

link. The quality of the link is continuously monitored for each handover request in the queue to update its position.

We introduce here an alternative priority scheme called last useful instant (LUI): this discipline relies on the fact that, when a handover request is queued, the system exactly estimates its $t_{w\,\max}$. A new request is stored in a queue position before (after) all handover requests having a greater (lower) residual value of $t_{w\,\max}$ [31]. In such a way, the system tries to serve first the most urgent handover request. We can note that the ideal LUI scheme represents the best scheduling strategy for handover requests [31].

The LUI queuing scheme described above has to be regarded as an ideal scheme, because it is based on an exact estimate of time $t_{w\,\max}$. The performance of the MBPS technique may be made very close to that of the ideal LUI scheme if the power level measures of the queued handovers are updated according to a suitable frequency.

A practical implementation of the LUI scheme in LEO-MSS's may be based on the use of a suitable positioning system which estimates the MS position at the beginning of the call and tracks the MS position during call lifetime.[5] Therefore, time $t_{w\,\max}$ can be obtained from (35), since the system knows both the relative MS-satellite motion and the cellular coverage geometry. We can consider that the MS position can be estimated by the LEO-MSS by measuring the propagation delay and Doppler frequency shift for the MS transmissions (i.e., a positioning system integrated into the LEO-MSS [32]). Using the time delay measurement, a fixed propagation delay circle is obtained on the earth. Since the Doppler frequency shift is related to the angle between the satellite velocity vector and the MS-satellite direction vector, the Doppler measurement defines a cone making a fixed angle with the satellite velocity vector. The intersection on the earth between the constant propagation delay circle and the cone identifies two points. A possible solution to solve this spatial ambiguity is to take another Doppler frequency shift measurement from a second satellite in visibility (this solution adds some constraints on the satellite constellation).

It is important to highlight that this implementation of the LUI strategy in LEO-MSS's appears to be less complex than the MBPS approach because it avoids the continuous monitoring of the signal level received by the satellite for each call with a queued handover request and, hence, the continuous ranking of the queued handover requests.

D. Effectiveness of the LUI Queuing Scheme

The efficiency of the LUI queuing discipline as regards the FIFO one primarily depends on the spreading degree of the distribution of $t_{w\,\max}$ around its average value. As a matter of fact, if this distribution tends to a deterministic value, the LUI discipline approaches the FIFO one. Note that the distribution of $t_{w\,\max}$ depends on the hypotheses made on both mobility and overlap areas.

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[5] Once a first MS position measurement has been taken, the MS position can be tracked by estimating position variations on the basis of satellite ephemerides (this is possible because, in the LEO case, the relative satellite-MS motion is dominated by the satellite motion).

Moreover, the efficiency of the LUI discipline also depends on both the mobility coefficient α and the congestion degree of the system. If the user mobility decreases, the time spent in the overlap area increases; then, the ordering made by the LUI scheme among the queued handover requests becomes more efficient. In addition to this, if the congestion of a cell decreases, on average, the occupancy of the handover queue decreases, so the queuing discipline has a reduced impact on system performance.

As for the management of the queued handover requests, FCA-QH and DCA-QH are significantly different, and this has an impact on the performance of the LUI scheme as regards the FIFO one, as shown in Section VIII.

VII. ANALYSIS OF FCA-QH WITH DIFFERENT QUEUING STRATEGIES

In this section, an analytical approach for evaluating the FCA-QH performance is considered; it is based on the following assumptions and approximations.

- S channels are assigned per cell according to (30).
- New call arrivals and handover attempts are two independent Poisson processes,[6] with mean rates λ and λ_h, with λ_h related to λ by (25).
- The statistical distribution of the channel holding time in a cell (both for new call arrivals and handovers) is approximated by an exponential distribution with mean value, $1/\mu$, obtained as

$$\frac{1}{\mu} = \frac{\lambda(1 - P_{b1})}{\lambda(1 - P_{b1}) + \lambda_h(1 - P_{b2})} E[t_{H1}]$$
$$+ \frac{\lambda_h(1 - P_{b2})}{\lambda(1 - P_{b1}) + \lambda_h(1 - P_{b2})} E[t_{H2}] \quad (42)$$

where $E[t_{H1}]$ and $E[t_{H2}]$ are derived from (15).

- The maximum waiting time is approximated as a random variable exponentially distributed, with expected value $1/\mu_w$ given by (40).
- The queue length is infinite.

From above, we have that each cell can be modeled as an $M/M/S$ queuing system with nonhomogeneous arrival rates [14], [16], [17] (M: Poisson arrival process/M: service time exponentially distributed/S: number of channels assigned per cell), as shown in Fig. 5. The state of this queuing system is given by the sum of the number of calls in service and the number of queued handover requests. Whenever the system is in a state n less than S, the gross arrival rate is $\lambda + \lambda_h$; while, if the state is greater than or equal to S (i.e., all channels are busy), the gross arrival rate is λ_h. Moreover, we have considered that a call may end in the overlap area before obtaining service and before its maximum queuing time has expired [29]. Accordingly, the Markov chain in Fig. 5 contains additional death rates $i\mu$ for the states $S+i$, with $i = 1, 2, \cdots$,

[6] A generalization of this analytical study to different arrival processes for handover requests, such as a bursty arrival process (e.g., suitable for modeling handover arrivals for public transportation systems), seems to be possible at the expense of a greater complexity [24]. However, in this case the main problem is to give an effective statistical characterization of the handover traffic in relation to specific scenarios. This study requires a deep investigation which is beyond the scope of this paper and has been left to a further study.
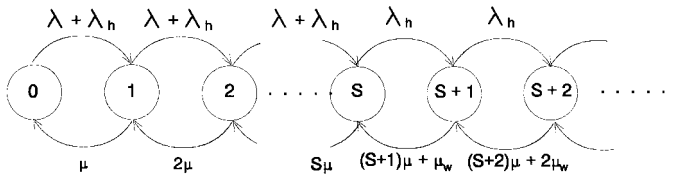

Fig. 5. The queuing system for FCA-QH.

as regards the model appeared in [14]. The Markov chain shown in Fig. 5 is valid for both FIFO and LUI disciplines. The probability of state n, P_n, is

$$P_n =$$
$$\begin{cases} \dfrac{(\lambda + \lambda_h)^n}{n!\mu^n} P_0, & 1 \leq n \leq S - 1 \\[2ex] \dfrac{(\lambda + \lambda_h)^S \lambda_h^{n-S}}{S!\mu^S \displaystyle\prod_{j=1}^{n-S} ((S+j)\mu + j\mu_w)} P_0, & n \geq S \end{cases}$$
$$(43)$$

where the idle system probability P_0 is

$$P_0 = \left\{ \sum_{n=0}^{S-1} \left[\frac{(\lambda + \lambda_h)^n}{n!\mu^n} \right] \right.$$
$$\left. + \sum_{n=S}^{\infty} \left[\frac{(\lambda + \lambda_h)^S \lambda_h^{n-S}}{S!\mu^S \displaystyle\prod_{j=1}^{n-S} ((S+j)\mu + j\mu_w)} \right] \right\}^{-1}. \quad (44)$$

New call arrivals are blocked when all the available channels are in use, i.e., when the queuing system is in the state $n \geq S$. Therefore, P_{b1} results in

$$P_{b1} = \sum_{N=S}^{\infty} P_n. \quad (45)$$

The blocking parameter P_{b1} does not depend on the queuing discipline. This statement has been verified by means of computer simulations (see the next section). Whereas P_{b2} depends on the queuing policy.

With the FIFO queuing discipline, P_{b2} can be derived by the approach outlined in [14] and [17] and by taking the following into account.

1) P_{b2} must contain, as a multiplying factor, the probability that the call, with a queued handover request, does not end before $t_{w\,\max}$ has expired, P_{uh}. According to the exponential distributions for the maximum queuing time and the channel holding time, P_{uh} is

$$P_{uh} = \frac{\mu_w}{\mu + \mu_w}. \quad (46)$$

2) State probabilities are given by (43) and (44).

3) We consider the additional departure rates $i\mu$ for states $S + i$ with $i = 1, 2, \cdots$, due to calls that end in the overlap area before accomplishing the related handover procedures.

Hence, we have

$$P_{b2} = \frac{\mu_w}{\mu + \mu_w} \sum_{n=S}^{\infty} P_n \left\{ 1 - \frac{S\mu}{S\mu + \mu_w} \right. $$
$$\left. \cdot \prod_{j=1}^{n-S} \left[1 - \frac{\mu_w}{S\mu + \mu_w} \left(\frac{\mu_w}{\mu + \mu_w} \frac{1}{2} \right)^j \right] \right\}. \quad (47)$$

With the LUI strategy, each handover request in the queue reaches the head of the queue, unless the request leaves the queue because the related call is ended. Hence, only the handover request at the head of the queue may fail. Therefore, the failure probability for a handover request that initially reaches the queue at position n $(>S)$ does not depend on n; let us denote by $P_{b2|S}$ this handover failure probability. Then, by using (45), the following result is obtained:

$$P_{b2} = \sum_{n=S}^{\infty} P_n P_{b2|S} = P_{b2|S} P_{b1}. \quad (48)$$

$P_{b2|S}$ takes into account two joint and independent events.

1) The call, whose handover request is at the head of the queue, does not end before its maximum queuing time has expired; the probability of this event is P_{uh}.

2) None of the S channels of the cell becomes free before the maximum queuing time has expired. Let us denote the probability of this event by P_f. According to the exponential distributions for the maximum queuing time and the channel holding time, we have

$$P_f = \frac{\mu_w}{S\mu + \mu_w}. \quad (49)$$

In conclusion, in the LUI case, P_{b2} is given by

$$P_{b2} = P_{b1} \frac{\mu_w}{\mu + \mu_w} \frac{\mu_w}{S\mu + \mu_w}. \quad (50)$$

Note that a recursive approach is necessary to compute P_{b1} and P_{b2} (for both queuing disciplines) as functions of λ, because λ_h depends on both P_{b1} and P_{b2}, according to (25). In order to speed up the convergence, the iterative method is not based on the two parameters P_{b1} and P_{b2}, as proposed in [14], but only on parameter $n_h = \lambda_h/\lambda$, which is a function of P_{b1} and P_{b2}.

We start the iterations with the value of n_h obtained from (25) and (26) with $P_{b1} = P_{b2} = 0$ (this is the maximum value of n_h; n_h decreases for increasing values of P_{b1} or P_{b2}). With such a value of n_h, μ, and P_n for $n = 0, 1, \cdots$, are computed according to (42)–(44). These values are used to derive P_{b1} and P_{b2} and, then, the new value of n_h. This value is averaged with that used at the previous step. A new iteration starts with this mean value of n_h. The iterative method is stopped when the relative difference between the n_h values computed in two subsequent steps is below a given threshold (i.e., 10^{-3}). Finally, we can derive P_{ns} from (29).
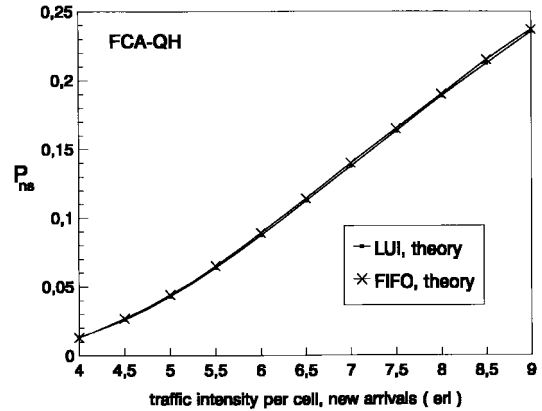

Fig. 6. Theoretic comparison between the performance of FIFO and LUI queuing disciplines for FCA-QH in terms of P_{ns} (IRIDIUM case, $S = 10$).

Fig. 6 highlights the analytical results concerning FCA-QH with FIFO and LUI schemes in the IRIDIUM case with $S = 10$. We note that the LUI strategy slightly outperforms the FIFO one. This result can be justified by considering that the time spent in the overlap area by an MS is so small (on average 7 s) that, in the queue of each cell, there is not a significant difference between serving either the most urgent handover request or the oldest one. A different impact of the LUI scheme will be highlighted in the next section by considering DCA-QH.

VIII. SIMULATION RESULTS

In obtaining our simulation results, we have removed all the simplifications made in the previous section in order to analytically derive the FCA-QH performance. In particular, we have used the models for mobility and overlap areas shown in Sections III and VI, respectively. Circular cells are considered for the resource management strategies based on handover queuing; whereas hexagonal cells are used for assignment strategies with the NPS scheme. The parameter values used in the simulations are:

- the average call duration is $T_m = 3$ min;
- the reuse distance is $D = \sqrt{21}R$;
- the simulated cellular network is parallelogram shaped and folded onto itself[7] with seven cells per side,
- a number of 70 channels is available to the system; then, ten channels/cell are available with FCA;
- the IRIDIUM mobility case is considered (i.e., $\alpha \approx 0.27$).

Moreover, we have assumed an infinite queue capacity for handover requests. Since theoretic results in Fig. 6 have revealed that the performance difference between LUI and FIFO queuing schemes is very little, simulation results have been gathered after very long simulation runs that allow 5% confidence intervals for the blocking results [33].

In Fig. 7(a) and (b), we can note that the analytical predictions for FCA-QH with both queuing disciplines give a conservative estimate of P_{ns} in comparison with simulation results. This difference is exclusively due to the simplifications

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[7]The parallelogram-shaped network we have simulated has been folded onto itself [15]. Therefore, handover requests are naturally generated for border cells and each cell has a complete set of adjacent cells as in the real three-dimensional global coverage satellite cellular system.
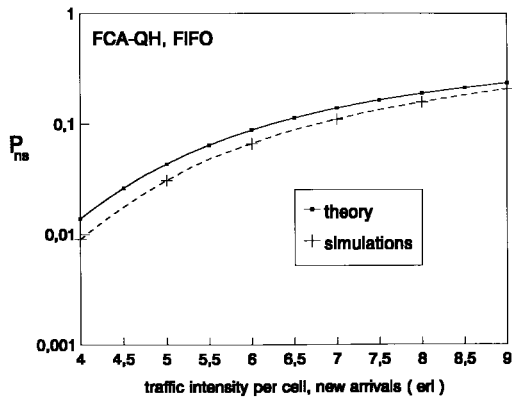
(a)
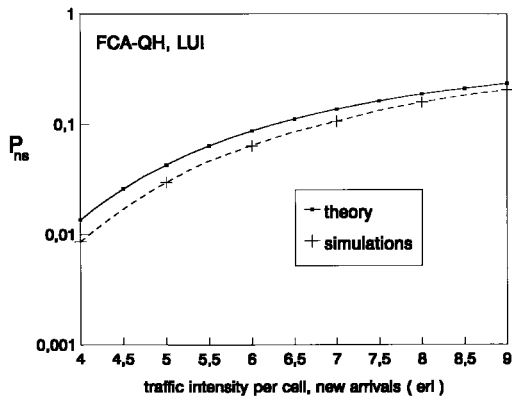
(b)

Fig. 7. (a) FCA-QH with FIFO queuing discipline: comparison between simulation and analytical predictions (IRIDIUM case, $S = 10$). (b) FCA-QH with LUI queuing discipline: comparison between simulation and analytical predictions (IRIDIUM case, $S = 10$).

Fig. 8. P_{b1} performance for FCA NPS and DCA NPS, FCA-QH and DCA-QH both FIFO and LUI (IRIDIUM case).
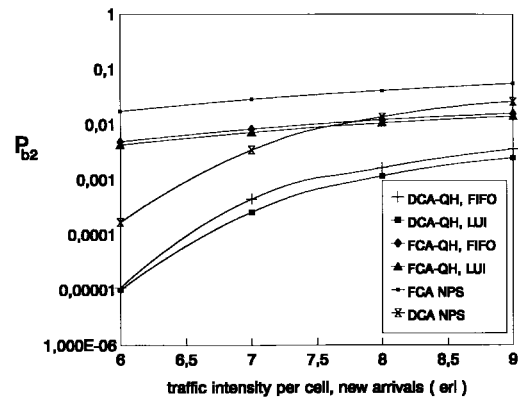
Fig. 9. P_{b2} performance for FCA NPS and DCA NPS, FCA-QH and DCA-QH both FIFO and LUI (IRIDIUM case).

assumed in our analysis for both the pdf of $t_{w\,\mathrm{max}}$, the handover arrival process, and the pdf of the channel holding time.

Let us remember that the ITU-T requirements for the quality of service parameters are $P_{b1} \leq 10^{-2}$ and $P_{\mathrm{drop}} \leq 5 \cdot 10^{-4}$ [22]. Referring to the IRIDIUM mobility conditions, we have $n_h' < 5$ handovers/call [see (27)]. Hence, on the basis of (28), the ITU-T requirement on P_{drop} is fulfilled if $P_{b2} \leq 10^{-4}$. We are interested in evaluating the maximum traffic intensity per cell due to new call arrivals (i.e., λT_m) that allows $P_{b1} \leq 10^{-2}$ and $P_{b2} \leq 10^{-4}$. This traffic load will be converted into capacity per cell (i.e., the maximum number of users per cell) by assuming that each user generates 0.025 erl of traffic [14]. Let us comment on the simulation results shown in Figs. 8–10.

A. DCA versus FCA

From Figs. 8 and 9 we note that the more critical requirement (i.e., the requirement that mostly limits the system capacity) is that on P_{b2}. None of the considered FCA techniques (i.e., FCA NPS, FCA-QH FIFO, and FCA-QH LUI) fulfills the requirements on P_{b1} and P_{b2} in the traffic range under examination. According to Table I, DCA techniques attain significantly better results in terms of maximum traffic intensity per cell and capacity per cell; moreover, DCA-QH
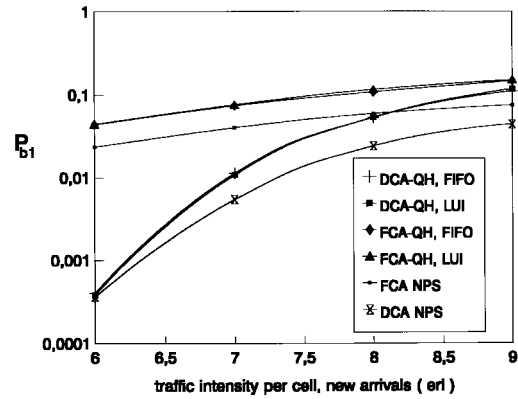
LUI achieves the highest system capacity among the resource management strategies considered in this paper.

B. NPS versus QH

As regards the NPS scheme, the QH strategy (regardless of both the queuing discipline and the channel allocation technique used) allows a significant reduction of P_{b2} at the expense of an increased value of P_{b1}. The advantages of QH schemes are particularly evident in terms of P_{ns}, as shown in Fig. 10.

C. FIFO versus LUI

Numerical results derived by means of computer simulations for both FCA-QH and DCA-QH have confirmed that P_{b1} (Fig. 8) is independent of the adopted queuing discipline (i.e., FIFO or LUI).

Let us refer to the behavior of P_{b2} shown in Fig. 9. With FCA-QH, the advantages of the LUI discipline with respect to the FIFO one are practically negligible. Whereas in the case of DCA-QH, the LUI scheme permits the reduction of P_{b2} as regards the FIFO policy. The reason for these different behaviors has to be searched in the way the handover queuing is managed by FCA-QH and DCA-QH. With FCA-QH, each cell has its queue, whereas DCA-QH requires that the system
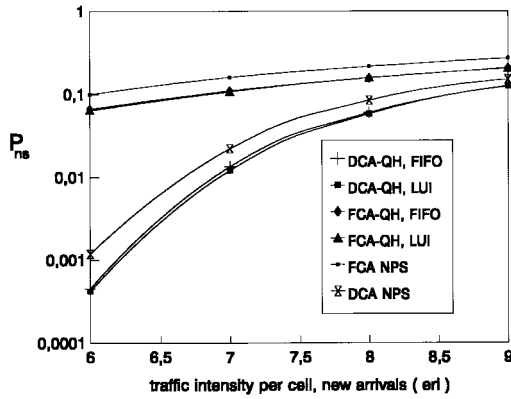
Fig. 10. P_{ns} performance for FCA NPS and DCA NPS, FCA-QH and DCA-QH both FIFO and LUI (IRIDIUM case).

TABLE I
DCA TECHNIQUES PERFORMANCE IN TERMS OF
MAXIMUM TRAFFIC INTENSITY AND CAPACITY

DCA technique	maximum traffic intensity per cell due to new call arrivals (erl)	capacity per cell (#users/cell)
DCA NPS	6	240
DCA-QH FIFO	6.6	264
DCA-QH LUI	6.8	272

(a)

(b)

Fig. 11. (a) Traffic forecast on the earth for future MSS's; each point is the traffic in erlang related to a $5°$ longitude $\times$ $5°$ latitude wide area. (b) Comparison of DCA-QH and FCA-QH in terms of P_{ns} for the traffic situation around the meridian of $10°$ E longitude.

manages a virtual global queue[8] formed by the handover requests waiting for service in all the cells. This global queue contains a greater number of handover requests than each single queue of FCA-QH. Hence, a specific ordering discipline has a greater impact on DCA-QH rather than on FCA-QH. This is a further advantage of the DCA approach as regards the FCA one.

D. Nonuniform Traffic Loads

In order to highlight that the advantages of the DCA scheme over the FCA approach can be enhanced in the case of nonuniform traffic, we have considered here the traffic model for LEO-MSS's proposed in [25]. In particular, the study presented in [25] has allowed us to forecast a traffic distribution on the earth that has been divided in areas of $5°$ longitude $\times$ $5°$ latitude. This traffic distribution [see Fig. 11(a)] has been obtained by assuming $T_m = 2$ min. Based on this result, Fig. 11(b) shows a performance comparison in terms of P_{ns} between DCA-QH and FCA-QH with the FIFO queuing for handover requests. These results have been obtained by assuming the system parameter values given at the beginning of this section (with the exception of $T_m = 2$ min). From Fig. 11(b) it is evident that the advantages of DCA-QH with respect to FCA-QH can be magnified in the case of nonuniform traffic.

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[8] Since with DCA NPS (and DCA-QH) the availability of a channel in a cell depends on the state of this channel in all the interfering cells, all the cells are interdependent in managing the queued handover requests.
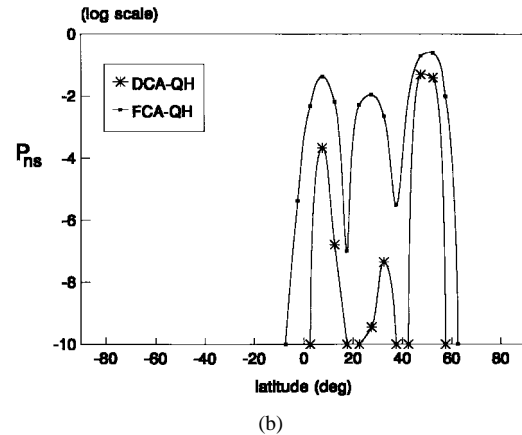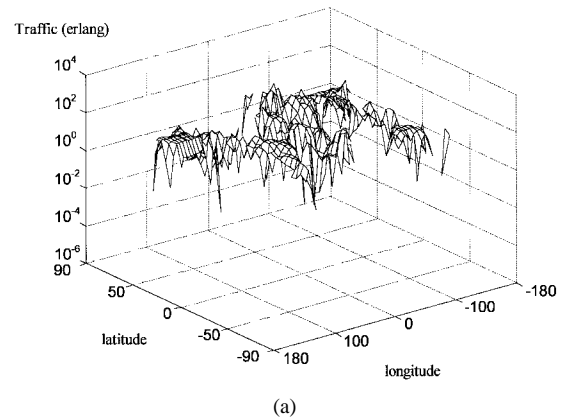
IX. CONCLUSIONS

This paper has presented a mobility model suitable for performance evaluation of channel allocation strategies in LEO-MSS's. Such a mobility model permits the removal of the approximation made in previous works of neglecting the motion of MS's along the seam of the cellular network and, hence, the increase of the accuracy of the performance evaluation. We have discussed this aspect which is of particular importance in LEO-MSS's, where interbeam handovers are very frequent during call lifetime.

In order to reduce the handover failure probability, the service of handover requests must be prioritized as regards that of new call attempts. Therefore, we have considered two different handover queuing schemes: i.e., FIFO and LUI. In particular, for the novel LUI approach a practical implementation has also been discussed and compared with that of the MBPS queuing scheme, previously presented in the literature.

Performance evaluations and comparisons have been carried out in terms of QoS parameters specified in the ITU-T Recommendation E.771. In particular, we have proved by simulations that the DCA technique outperforms the corresponding FCA one, it does not matter which handover prioritization scheme is adopted. Moreover, we have briefly proved that this advantage is increased with nonuniform traffic. Finally, we have shown that DCA-QH with the LUI queuing discipline allows a high

system capacity and, hence, it is a very attractive scheme for LEO-MSS's.

ACKNOWLEDGMENT

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