Queuing of Handover Requests in Low Earth Orbit Mobile Satellite Systems

Enrico Del Re, Romano Fantacci, Giovanni Giambene

Dipartimento di Ingegneria Elettronica - Università di Firenze

Via S. Marta, 3 - 50139 Firenze, Italy

Tel. +39 55 4796 285 - Fax +39 55 4796 485 - e-mail: delre@cosimo.die.unifi.it

ABSTRACT - *This paper deals with a study on resource management strategies in Low Earth Orbit Mobile Satellite Systems (LEO-MSSs). A suitable mobility model has been proposed. Fixed Channel Allocation (FCA) has been considered. Moreover, we have foreseen that inter-beam handover requests, which do not immediately find service, can be queued in order to reduce the handover failure rate. An analytical approach has been developed to compare two different queuing disciplines and its results have been compared with simulations.*

I. INTRODUCTION

Future global-coverage Mobile Satellite Systems (MSSs) will be able to provide the users with communication services anywhere and at anytime [1]. In particular, Low Earth Orbit (LEO) satellites will represent a very attracting solution. The study here presented is kept general and numerically illustrated in the case of the IRIDIUM system [2].

Only voice traffic has been considered; as in the classical fixed telephony, new call attempts that do not immediately find free resources are blocked and lost. A channel request in a beam x (=cell of the satellite system) may be due to either a new call arrival or a handover request from an adjacent beam (i.e., an active Mobile Station -MS- that moves from a cell towards an adjacent one); if no channel is available in x, the channel request fails and the relative call is dropped. From the user standpoint, it is more unacceptable the interruption of a conversation than the blocking of a newly arriving call. Moreover, inter-beam handover requests are extremely frequent during call lifetime in LEO-MSSs. Therefore, techniques that prioritize handover requests with respect to new call attempts are needed in order to reduce as much as possible the call dropping probability. A handover prioritization strategy based on the queuing of handovers, that do not attain immediately service, is considered here [3]: any handover request, that occurs in a congested cell, can be queued for a maximum time. In this study, two different queuing disciplines for handover requests have been compared in terms of

- the blocking probability for new call attempts, P_{b1}
- the handover failure probability, P_{b2}
- the call dropping probability, P_{drop}
- the probability P_{ns} that a call is not completely served due to either the initial blocking of the call attempt or the failure of a subsequent handover request.

According to ITU-T requirements, the values of P_{drop} and P_{b1} should not exceed 5 x 10^{-4} and 10^{-2}, respectively [4].

In the following, FCA-QH will denote the Fixed Channel Allocation with the Queuing of Handover requests [3].

II. PRELIMINARY CONSIDERATIONS AND ASSUMPTIONS ON LEO-MSSs

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'. Possible values for the ratio R'/R range from 1 to 1.5 [5]. Obviously, the greater this ratio is, the larger the *overlap area* between adjacent cells is and, then, the better the queuing technique performance is. In this paper, the minimum possible overlap area extension has been considered (Fig. 1): $R = R'$. In the IRIDIUM case under examination, it has been used $R = 212.5$ km.

Due to the high value of the satellite ground-track speed, V_{trk} (about 26,000 km/h in the LEO case) with respect to the other motion component speeds (i.e., the earth rotation around its axis and the user motion relative to the earth), the relative satellite-user motion can be approximated by only vector V_{trk} [6].

Two different cells on the earth may reuse the same channel provided that they are at a suitable distance, called *reuse distance* D, that allows tolerable levels for the co-channel interference. In this paper, it will be assumed that $D = \sqrt{21} \ R$.

III. THE LEO MOBILITY MODEL AND ANALYSIS OF ITS STATISTICAL PARAMETERS

Let us denote by *source cell*, the cell where the MS call starts and *transit cell* any subsequent cell reached by the MS with the call in progress. Let us consider an MS that crosses a source cell at a height $z \in [-R, R]$ (Fig. 1). Let $r(z)$ denote the length of the circular cell with radius R at a height z (Fig. 1):

$$r(z) = 2\sqrt{R^2 - z^2} \tag{1}$$

The circular cell is divided into two regions: the overlap area between adjacent cells in the direction of the relative motion and the part of the cell that is called *curvilinear cell* (whose area is equal to $3\sqrt{3} \ R^2 /2$); this cell is represented by the shaded area in Fig. 1. The MS crosses a distance $h(z)$ in the curvilinear cell and a distance $o(z)$ in the overlap area:

$$h(z) = r(z) - o(z) \qquad (2)$$

and

$$o(z) = \begin{cases} 2\sqrt{R^2 - z^2} - \sqrt{3}\,R, & \text{if } |z| \le \dfrac{R}{2} \\[12pt] \sqrt{R^2 - z^2} - \dfrac{\sqrt{3}}{2}R + \sqrt{R^2 - \left(|z| - \dfrac{3}{2}R\right)^2}, & \text{if } R \ge |z| > \dfrac{R}{2} \end{cases} \qquad (3)$$

Fig. 1: The geometry assumed for the overlap areas.

The distance $o(z)$ covered in the overlap area is obtained from (3) and, due to the geometry of the problem (see also the following assumptions on mobility), this value is valid for any subsequent handover request. The LEO mobility model proposed in this paper is the following one:

- MSs cross the cellular network with a relative velocity, vector V_{trk}, "orthogonal" to the side of the cells (Fig. 1).

- When a handover occurs, the destination cell is the neighboring cell in the direction of the relative satellite-user motion.

- Calls are uniformly generated all over the network.

- From the call outset in a cell, an MS travels a distance (depending on z) defined as:

  - uniformly distributed between 0 and $h(z)$, if the call is in its *source cell*;

  - deterministically equal to $h(z)$, if the call is in a *transit cell*.

According to these assumptions, the probability density function (pdf) of the height z of a call arrival in a cell is $f_i(z)$, where $i = 1$ for the source cell and $i = 2$ for a transit cell:

$$f_i(z) = \begin{cases} \dfrac{h(z)}{\dfrac{3\sqrt{3}}{2}R^2}, & \text{if } i = 1 \\[16pt] \dfrac{u[z + R] - u[z - R]}{2R}, & \text{if } i = 2 \end{cases} \qquad (4)$$

where:

$$u(x) = \begin{cases} 1, & x \ge 0 \\ 0, & \text{otherwise} \end{cases} \qquad (5)$$

We introduce the following dimensionless parameter that characterizes the MS mobility in a cell, according to height z:

$$\alpha(z) = \frac{h(z)}{V_{trk}\,T_m} \qquad (6)$$

where T_m is the average call duration.

For $|z| \le R/2$, $h(z) = \sqrt{3}\,R$ and $\alpha(z) = \sqrt{3}\,R/(V_{trk}\,T_m)$; this quantity will be denoted by α. For the IRIDIUM satellite constellation ($R=212.5$ km, $V_{trk}=26,600$ km/h), if $T_m=3$ min, α is about equal to 0.27.

The unencumbered call duration, t_d, has been assumed a random variable exponentially distributed with mean T_m. Let t_{mc1} (t_{mc2}) be the time interval elapsed from the arrival instant of a call in its source cell (transit cell) to the instant in which the related MS exits the cell. Handover probabilities P_{H1} and P_{H2} respectively from the source and the transit cell are obtained through the following formula [6]:

$$P_{Hi} = \int_{-R}^{R} P_{hi}(\alpha(z))\, f_i(z)\, dz \qquad (7)$$

where:

$$P_{h1}(x) = \frac{1 - e^{-x}}{x}, \qquad P_{h2}(x) = e^{-x} \qquad (8)$$

Handover probabilities P_{H1} and P_{H2} only depend on the mobility parameter α. It is evident that as α approaches 0 (∞), P_{H1} and P_{H2} approach 1 (0). In the IRIDIUM case, $P_{H1} \approx 89\%$ and $P_{H2} \approx 81\%$. The channel holding time in a cell can be derived as:

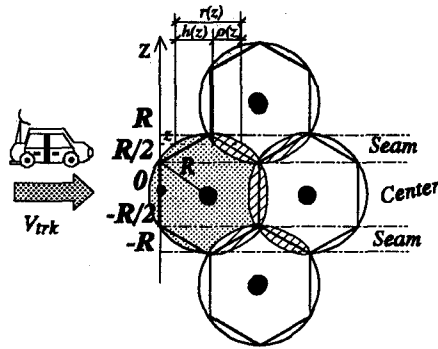$$t_{Hi} = \min[\,t_d\,,\, t_{mci}\,] \qquad (9)$$

where: $i = 1$, for the source cell, $i = 2$, for a transit cell.

From [7], the expected value of t_{Hi}, $E[t_{Hi}]$, results in:

$$E[t_{Hi}] = T_m(1 - P_{Hi}) \qquad (10)$$

Let us consider an MS that starts a call in the source cell at a height $z \in [-R, R]$; z is a random variable with probability distribution function $f_1(z)$ given by (4).

If $|z| \le R/2$ (Fig. 1), the MS motion is centered with

respect to the cellular network. Then, the mean number of handover requests for $|z| \leq R/2$ [6] is:

$$n_{h|z} = \frac{P_{hl}(\alpha)(1 - P_{bl})}{1 - (1 - P_{b2})P_{h2}(\alpha)} \quad , \quad for \ |z| \leq \frac{R}{2} \quad (11)$$

If $R \geq |z| > R/2$ (Fig. 1), the MS is moving across the seam of the cellular network; the maximum distance covered in the source cell is $h(z) = 2\sqrt{3}\,(R - |z|)$, whereas the distance crossed in the subsequent transit cell is $\sqrt{3}\,R - h(z)$. In the next transit cell the distance covered is again $h(z)$, and so on, alternately. Let us denote:

$$\alpha_1(z) = \frac{h(z)}{V_{trk}T_m} \quad , \quad \alpha_2(z) = \frac{\sqrt{3} - h(z)}{V_{trk}T_m} \quad (12)$$

The average number of handover requests per call for $R \geq |z| > R/2$ is given by:

$$n_{h|z} = (1 - P_{bl})\frac{P_{hl}(\alpha_1) + (1 - P_{b2})P_{hl}(\alpha_1)P_{h2}(\alpha_2)}{1 - (1 - P_{b2})^2 P_{h2}(\alpha)} \quad (13)$$

The average number of handover requests can be obtained by removing the conditioning on z in formulas (11) and (13) with the pdf of z, i.e., $f_i(z)$, from $-R$ to R; we have:

$$n_h = \frac{2(1 - P_{bl})}{3}\left\{\frac{P_{hl}(\alpha)}{1 - (1 - P_{b2})P_{h2}(\alpha)} + \frac{P_{hl}(\alpha) - P_{b2}\zeta(\alpha)}{1 - (1 - P_{b2})^2 P_{h2}(\alpha)}\right\}$$

$$(14)$$

where:

$$\zeta(\alpha) = \frac{2}{\alpha}\left(P_{H2}(\alpha) - P_{h2}(\alpha)\right) \quad (15)$$

The average number of handover requests per served call, $n_h{}'$, can be obtained from n_h through the following formula:

$$n_h' = \frac{n_h}{1 - P_{bl}} \quad (16)$$

If a served call originates an average number $n_h{}'$ of handover requests and at each request the call may be dropped with probability P_{b2}, then the overall call dropping probability is given by:

$$P_{drop} = n_h' P_{b2} \quad (17)$$

Probability P_{ns} can be obtained as follows [3, 6]:

$$P_{ns} = P_{bl} + (1 - P_{bl})\,P_{drop} = P_{bl} + n_h P_{b2} \quad (18)$$

λ_h is the average arrival rate of handover requests towards a generic cell. Whereas, λ is the average arrival rate of new call attempts in a generic cell. We can use the following formula which is valid for any mobility model:

$$n_h = \frac{\lambda_h}{\lambda} \quad (19)$$

IV. HANDOVER QUEUING POLICIES

In order to meet the specified requirements for the call dropping probability, the Queuing of Handover requests (QH) is here utilized when no channel is free in the destination cell of the mobile at the handover request instant.

Let us assume that an active MS is approaching the borders of its cell x and is going into an adjacent cell y. The MS sends a handover request as soon as the level of the received signal drops below a given threshold. In this paper, we consider that this event corresponds to the instant in which the MS enters the overlap area between cell x and cell y. In cell y, the MS must be provided with a new channel to carry on the communication. The MS crosses the overlap area in a time t_{wmax}. If no channel is immediately available in cell y, the handover request can be queued for a maximum time t_{wmax}, to wait that a resource becomes free [6]. According to the mobility assumptions, t_{wmax} is given by:

$$t_{wmax} = \frac{o(z)}{V_{trk}} \quad (20)$$

The average value of the maximum queuing time, $E[t_{wmax}]$, results in:

$$E[t_{wmax}] = \alpha\,T_m\,\beta \quad (21)$$

where the dimensionless parameter β is given by:

$$\beta = \frac{4}{9}\left(\frac{\sqrt{3}}{3}\pi - \frac{3}{2}\right) \approx 0.1394 \quad (22)$$

In the IRIDIUM case, we have: $E[o(z)] \approx 52$ km and $E[t_{wmax}] \approx 7$ s, and, according to (14) $n_h \approx 4.9$, for $P_{bl} = P_{b2} = 0$.

Depending on the service order for the queued handover requests, two schemes have been considered in this paper: the First Input First Output (FIFO) and the "*Last Useful Instant*" (LUI) technique. In the FIFO scheme [3, 6], handover requests are queued according to their arrival instants. Whereas, the idealized queuing discipline called "*Last Useful Instant*" (LUI) requires that, when a handover request is queued, the system exactly knows its maximum queuing time (t_{wmax}). This new request is placed before the others found in the queue that have a greater residual maximum queuing time. In such a way, the system serves first the most critical handover request. The relative ranking of queued handover requests does not change while they are waiting for the service. A possible implementation of the LUI strategy is based on the estimation of t_{wmax} by measuring, with a sufficient accuracy, the position of the MS at the call arrival instant in the source cell (e.g., by a positioning system integrated into the MSS).

V. ANALYSIS OF FCA-QH WITH DIFFERENT QUEUING STRATEGIES

In performing the analysis on FCA-QH, we have assumed that:

- S channels are assigned per cell with FCA;

- new call arrivals and handover attempts are two independent Poisson processes, with mean rates λ and λ_h, with λ_h related to λ by (14) and (19);

- whether handover requests are queued or not, the channel holding time in a cell is approximated as exponentially distributed with mean $1/\mu$, expressed as:

$$\frac{1}{\mu} = \frac{\lambda(1-P_{b1})\,E[t_{H1}] + \lambda_h(1-P_{b2})\,E[t_{H2}]}{\lambda(1-P_{b1}) + \lambda_h(1-P_{b2})} \qquad (23)$$

where $E[t_{H1}]$ and $E[t_{H2}]$ are derived from (10);

- the maximum waiting time is approximated by a random variable exponentially distributed, with expected value equal to $1/\mu_w = E[t_{wmax}]$, where $E[t_{wmax}]$ is given by (21);

- the handover queue has an infinite capacity.

From the above assumptions it follows that in case of the FCA-QH technique each cell can be modelled as an $M/M/S$ queuing system (Fig. 2) with non-homogeneous arrival rates [6] (M: Poisson arrival process / M: service time exponentially distributed / S: number of channels assigned per cell).

The status of the queuing system under consideration (= a cell) has been defined as sum of the number of calls in service and the number of queued handovers. Whenever the system is in a status n less than S, the gross arrival rate is $\lambda + \lambda_h$; while, if the status is greater or equal to S, i.e. all channels are busy, the gross arrival rate is λ_h (Fig. 2). When the system is in the state $S+i$, for $i=1,2,\ldots$, we have added $i\mu$ to the departure rate with respect to the queuing model shown in [6] (Fig. 2), because a call may end in the overlap area before obtaining service. The model shown in Fig. 2 is valid for both FIFO and LUI queuing disciplines.
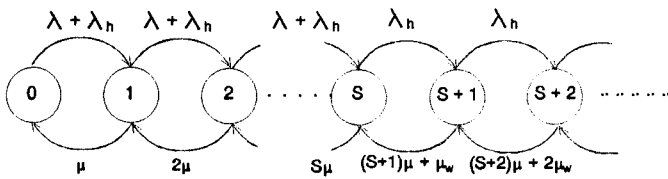

Fig. 2: The Markov chain model for a cell with FCA-QH.

Let us analyze the state probabilities for the Markov chain in Fig. 2; by following the same approach proposed in [6], the probability of state n, P_n, can be derived as:

$$P_n = \begin{cases} \dfrac{(\lambda + \lambda_h)^n}{n!\,\mu^n}\,P_0 \ , & 1 \le n \le S-1 \\[4mm] \dfrac{(\lambda + \lambda_h)^S\,\lambda_h^{\,n-S}}{S!\,\mu^S \displaystyle\prod_{j=1}^{n-S}\big((S+j)\mu + j\mu_w\big)}\,P_0 \ , & n \ge S \end{cases} \qquad (24)$$

where the idle system probability, P_0, is given by:

$$P_0 = \left\{ \sum_{n=0}^{S-1}\left[\frac{(\lambda + \lambda_h)^n}{n!\,\mu^n}\right] + \sum_{n=S}^{\infty}\left[\frac{(\lambda + \lambda_h)^S\,\lambda_h^{\,n-S}}{S!\,\mu^S \displaystyle\prod_{j=1}^{n-S}\big((S+j)\mu + j\mu_w\big)}\right] \right\} \qquad (25)$$

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

$$P_{b1} = \sum_{n=S}^{\infty} P_n \qquad (26)$$

The blocking parameter P_{b1} does not depend on the queuing discipline, whereas P_{b2} depends on the assumed queuing policy (i.e., FIFO or LUI).

In the FIFO case, P_{b2} can be derived by following the same approach proposed in [3, 6] and by considering these new aspects:

- P_{b2} must contain a multiplying factor $P_{uh} = \mu_w/(\mu + \mu_w)$ which represents the probability that the queued handover request is related to a call that does not end before its time t_{wmax} has expired.

- State probabilities are derived according to the new queuing model (Fig. 2).

- We take account of the additional departure rates $i\mu$ for states $S + i$ for $i = 1, 2, \ldots$

P_{b2} results in:

$$P_{b2} = \frac{\mu_w}{\mu + \mu_w} \cdot \qquad (27)$$

$$\sum_{n=S}^{\infty} P_n \left\{ 1 - \frac{S\mu}{S\mu + \mu_w} \prod_{j=1}^{n-S}\left[1 - \frac{\mu_w}{S\mu + \mu_w}\left(\frac{\mu_w}{\mu + \mu_w}\,\frac{1}{2}\right)^j \right] \right\}$$

In the LUI case strategy, P_{b2} can be derived as follows; each handover request in the queue reaches anyhow the head of the queue before dropping the associated call, unless the request leaves the queue because of a call termination. Only the call whose handover request is at the head of the queue may be dropped. Therefore, the probability of handover failure for a handover request, that is queued since it does not find any free resource among the S, $P_{b2|S}$, does not depend on the position that this request initially has in the queue. Then, by taking also into account (26), the following result is obtained:

$$P_{b2} = \sum_{n=S}^{\infty} P_n P_{b2|S} = P_{b2|S}\,P_{b1} \qquad (28)$$

$P_{b2|S}$ takes into account two joined and independent events:

- the call, whose handover request is at the head of the queue, does not end before exiting the overlap area (probability P_{uh}).

- None of the S channels of the cell becomes free before the maximum queuing time has expired (probability P_f).

By using the exponential distributions for the maximum queuing time and the channel holding time, we obtain the following results:

$$P_{uh} = \frac{\mu_w}{\mu + \mu_w} \quad , \quad P_f = \frac{\mu_w}{S\mu + \mu_w} \qquad (29)$$

Hence, in the LUI case, P_{b2} is given by:

$$P_{b2} = P_{b1} \frac{\mu_w}{\mu + \mu_w} \frac{\mu_w}{S\mu + \mu_w} \qquad (30)$$

An iterative method based on parameter n_h is needed to compute P_{b1} and P_{b2} (for both queuing disciplines), because λ_h is related to P_{b1} and P_{b2}, through (14) and (19). Finally, we obtain P_{ns} from (18).

VI. SIMULATION RESULTS

The following assumptions have been made for the simulations:

- the call arrival process is Poisson independent from cell to cell with average rate per cell equal to λ,

- the call duration is exponentially distributed with average value T_m equal to 3 min,

- the simulated cellular network is parallelogram shaped and folded onto itself with 7 cells per side,

- $S=10$ channels per cell with FCA,

- the IRIDIUM mobility case is considered ($\alpha \approx 0.27$),

- an infinite queue capacity is assumed.

The comparisons between simulation and analytical results for FCA-QH with FIFO and LUI queuing disciplines are respectively shown in Fig. 3 and 4 in terms of parameter P_{ns}.
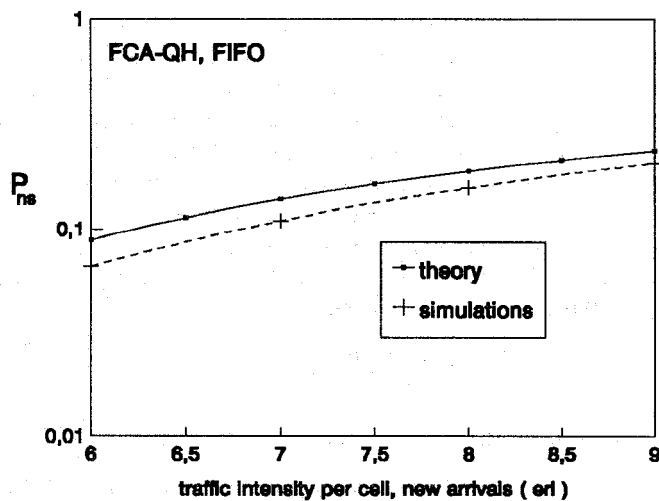

Fig. 3: FCA-QH and FIFO queuing discipline (IRIDIUM case).
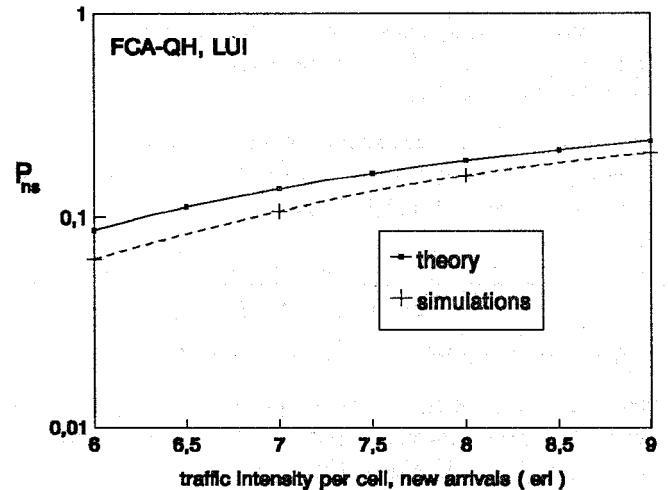

Fig. 4: FCA-QH and LUI queuing discipline (IRIDIUM case).

In these figures, we may note that the theoretic approaches for both queuing disciplines give a conservative estimate of the P_{ns} performance obtained by simulations. We may note that the LUI discipline permits to achieve only a negligible advantage with respect to the FIFO one (in terms of P_{ns}).

VII. CONCLUSIONS

A LEO-MSS has been assumed and a suitable mobility model has been proposed. FCA has been considered with two handover queuing disciplines: the FIFO scheme and the idealized LUI technique. It has been considered that the queuing of handover requests is essential to improve the performance of high mobility systems such as LEO-MSSs. Then, we have shown that the FIFO policy attains good results very close to those of the LUI technique. Therefore, the FIFO solution has to be preferred to the LUI one, that requires a greater implementation complexity.

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