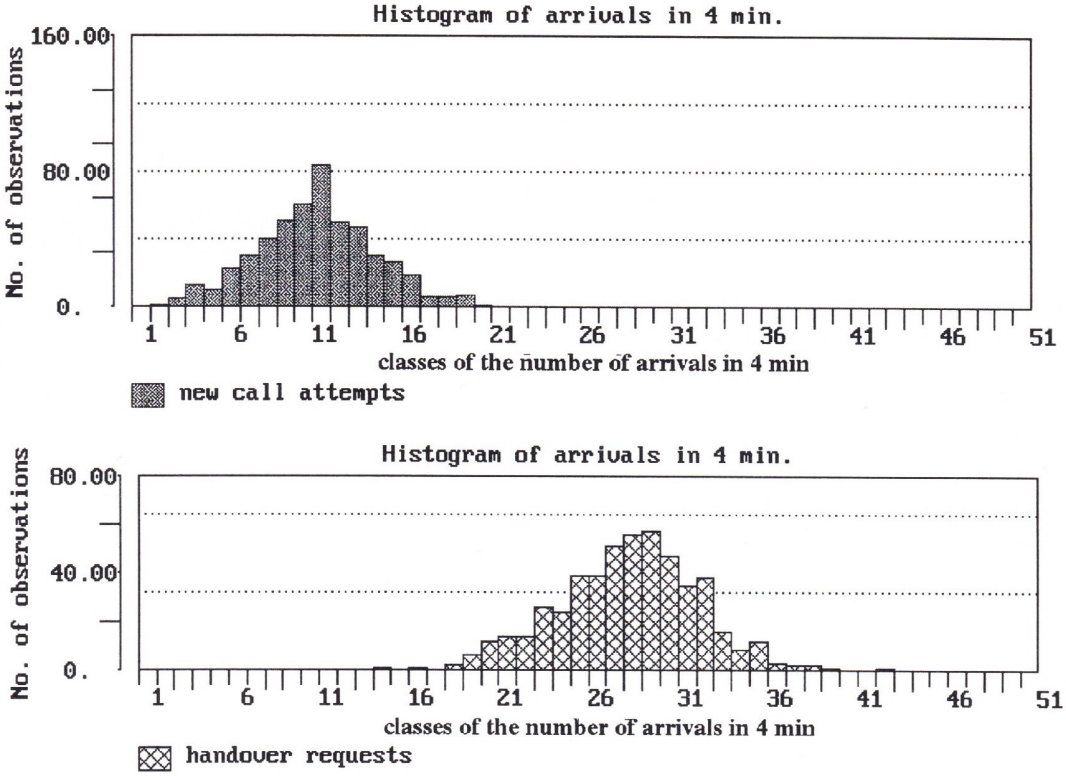

Figure 8. Histograms for the number of both handover arrivals and new call arrivals in 4 min in a cell for a LEO-MSS (IRIDIUM case, $\alpha = 0.16$) with FCA and DCA and a traffic intensity of 8 erl/cell due to new call attempts.

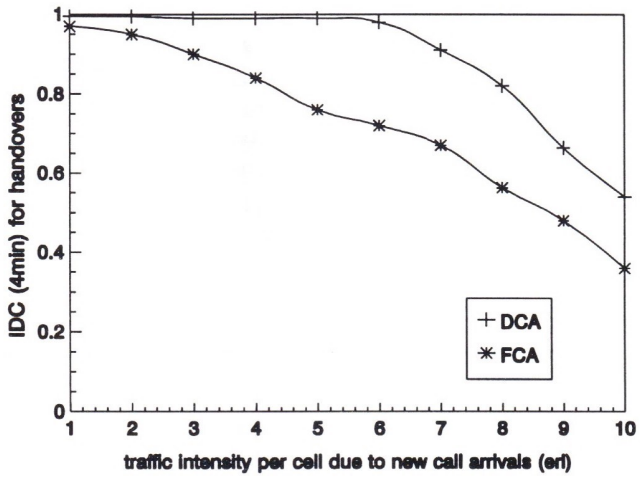

Figure 9. Behaviors of $\mathrm{IDC}_{t=4\ \mathrm{min}}$ for the handover arrival process towards a cell as a function of the traffic intensity due to new call arrivals for a LEO-MSS (IRIDIUM case, $\alpha = 0.16$) with FCA and DCA.

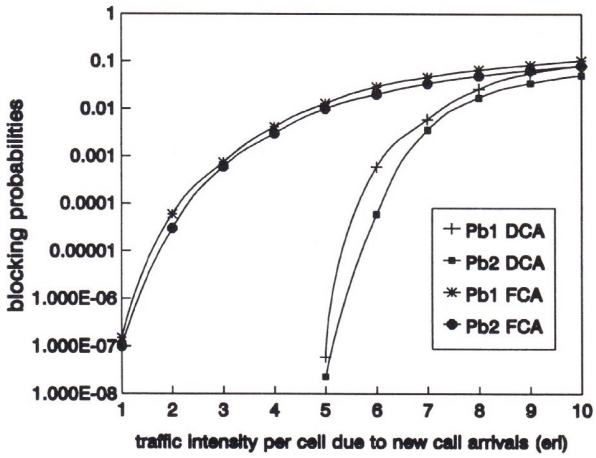

Figure 10. Behaviors of P_{b1} and P_{b2} for a LEO-MSS (IRIDIUM case, $\alpha = 0.16$) with FCA and DCA as a function of the traffic intensity per cell due to new call attempts.

ure 10 by assuming IRIDIUM-like conditions (i.e., $\alpha = 0.16$). The channel allocation techniques are both FCA and DCA [9,10]. Very long simulation runs have been performed in order to achieve reliable results. Figure 10 shows that DCA attains a better performance than FCA in terms of both P_{b1} and P_{b2}. Moreover, both FCA and DCA yield $P_{b1} > P_{b2}$ (note that we have not considered any prioritization for handover requests with respect to new call attempts); this result confirms the smooth characteristics of the handover traffic. Analogous considerations have been drawn in [33] with a different mobility model.

7. Performance analysis

In this section we analyze the blocking performance of FCA without any prioritization for handover requests because this case permits highlighting the differences between P_{b1} and P_{b2} which are only due to the differences of the related input traffics. A theoretical evaluation of the block-

ing performance of DCA has been left to a further study, since it is quite complex and only approximated methods are available in the literature [2]. On the other hand, the purpose of this section is to show how the user mobility characterization made in section 5 can lead to a performance analysis where the differences between the new call arrival process and the handover arrival process are taken into account.

A cell with K channels is modeled as a K-server loss queuing system with two types of input traffic (i.e., heterogeneous traffic case): new call attempts and handover requests. The new call arrival process is Poisson; this is not true for the handover arrival process, as verified in the previous section.

The smooth handover arrival process gives a lower blocking probability than a Poisson one for the same traffic intensity (i.e., the product of the mean input arrival rate and the mean service time). Therefore, the Poisson assumption for the handover arrival process in a cell (i.e., ERLANG-B approach), which was made in [7,11], led to overestimate the blocking probabilities (especially P_{b2}) with respect to simulation results. A suitable model for a cell should be the $G/G/K/K$ loss queuing system (G: General arrival process/G: General service time distribution/K: number of servers per cell/K: number of places in the system). The exact analysis of such a system is very complex to be carried out in a closed form. Hence, we have resorted here to a simplified approach based on the standard methods of the teletraffic theory for telephone systems. In particular, we consider a two-moment characterization of the input traffic by means of the peakedness factor z [4,13] which is defined as the variance-to-mean ratio of the number of busy servers by assuming that this traffic is offered to a modified system with infinite servers. A smooth traffic has $z < 1$, whereas a Poisson traffic has $z = 1$. Differently from IDC, the peakedness factor cannot be easily estimated by simulations, since its derivation entails the use of a queuing system with infinite servers.

The peakedness factor approach for the approximated analysis of the blocking probability has been extended to the case of a general service time distribution in [13].

Since the total input process to the loss queuing system which models a cell is not Poisson, we have to distinguish between the *time congestion* (i.e., the probability that all resources are busy in a cell) and the *call congestion* (i.e., the probability that a channel demand is blocked due to a lack of available resources in a cell) [4].

In order to simplify our analysis we assume here that both new calls and handed-over calls have the same pdf of the channel holding time in a cell (expected value $E[t_H]$). Hence, both new calls and handed-over calls have the same handover probability, P_H, which is defined as follows:

$$P_H \triangleq \frac{\lambda(1-P_{b1})}{\lambda(1-P_{b1})+\lambda_h(1-P_{b2})}P_{H1} + \frac{\lambda_h(1-P_{b2})}{\lambda(1-P_{b1})+\lambda_h(1-P_{b2})}P_{H2}. \quad (32)$$

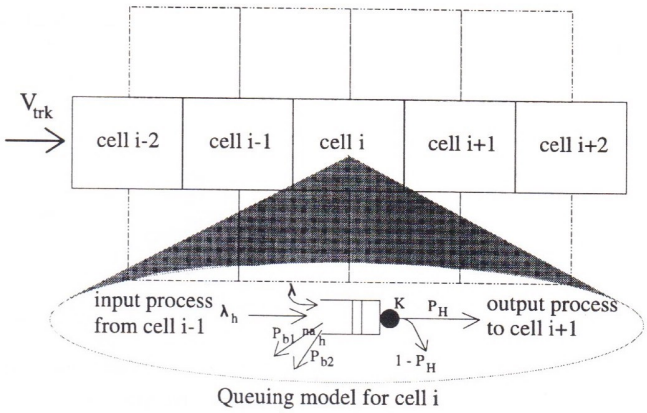

Figure 11. Modeling of a cell with FCA and BCC policy in the LEO mobility case as a loss queuing system and illustration of both input and output processes.

Since our analysis is based on the peakedness factor, it is sufficient to characterize only the expected value of the channel holding time in a cell, $E[t_H]$, that can be deduced from $E[t_{H1}]$ and $E[t_{H2}]$ in the same way as P_H is obtained from P_{H1} and P_{H2} in (32). Therefore, recalling (15), we have

$$E[t_H] = T_m(1 - P_H). \quad (33)$$

Finally, the flow balance condition (21) can be used to relate λ_h and λ, provided that we substitute P_H for both P_{H1} and P_{H2}; moreover, we use (23) in order to have that λ_h/λ is equal to n_h.

Referring to the LEO mobility model detailed in section 5, we have that handed-over calls from a given cell are addressed towards an adjacent cell in the direction of the relative satellite-user motion. Let us focus on the situation depicted in figure 11: a given cell i receives the input traffic of new call attempts and the handover traffic coming from the adjacent cell $i-1$. We consider the following peakedness factor characterization for the processes related to cell i:

- z_{na}, new call attempt input process ($z_{na} = 1$, because it is related to a Poisson process);
- $z_{h\text{-in}}$, handover input process: $z_{h\text{-in}} < 1$;
- $z_{h\text{-out}}$, handover output process (i.e., the handover input process for cell $i+1$);
- $z_{t\text{-in}}$, total input process;
- $z_{t\text{-out}}$, total output process (both calls ended in cell i and handed-over calls to cell $i+1$).

By assuming a cellular network folded onto itself to avoid border effects [9,10], we have that the total input process for cell i has the same characteristics of the total input process for cell $i+1$. Hence, the handover input process and the handover output process must have the same peakedness value for a generic cell i: $z_{h\text{-in}} = z_{h\text{-out}} = z_h$. This is an extension to the flow balance condition (21) which only states the equality between the first moments of these handover processes.

We consider that the two input processes to a given cell (i.e., new call attempts and handover requests) are independent, because the new call generation in a cell does not depend on the handover generation from the adjacent cell. Hence, we can relate $z_{\text{t-in}}$ to z_{h} according to the following result [4]:

$$z_{\text{t-in}} = \frac{1 + n_{\text{h}} z_{\text{h}}}{1 + n_{\text{h}}}. \tag{34}$$

In order to express z_{h} we take into account the splitting for the output process of the queuing system in figure 11. We make the reasonable approximation that this is a random splitting (i.e., we neglect any dependence of the handover generation process on the channel holding time in a cell). Therefore, the peakedness factor z_{h} can be related to $z_{\text{t-out}}$ as explained in [29]:

$$z_{\text{h}} = 1 - P_{\text{H}} + P_{\text{H}} z_{\text{t-out}}. \tag{35}$$

Finally, $z_{\text{t-out}}$ can be related to $z_{\text{t-in}}$ as considered in [13]:

$$z_{\text{t-out}} = z_{\text{t-in}} - \rho_{\text{o}} \frac{K - \rho_{\text{c}}}{\rho_{\text{c}}}, \tag{36}$$

where

- ρ_{c} is the total carried traffic of cell i:

$$\rho_{\text{c}} \triangleq \lambda E[t_{\text{H}}](1 - P_{\text{b1}}) + \lambda_{\text{h}} E[t_{\text{H}}](1 - P_{\text{b2}}),$$

- ρ_{o} is the total overflow traffic of cell i:

$$\rho_{\text{o}} \triangleq \lambda E[t_{\text{H}}] P_{\text{b1}} + \lambda_{\text{h}} E[t_{\text{H}}] P_{\text{b2}}.$$

Blocking probabilities P_{b1} and P_{b2} can be derived on the basis of the formulas proposed by Delbrouck in [4] for heterogeneous traffic, by taking into account the different peakedness values of the input traffic, z_{na} and z_{h}, as

$$\begin{aligned} P_{\text{b1}} &= \beta\left[1 + \frac{K}{\rho_{\text{t}}}(z_{\text{na}} - 1)\right] \equiv \beta, \\ P_{\text{b2}} &= \beta\left[1 + \frac{K}{\rho_{\text{t}}}(z_{\text{h}} - 1)\right], \end{aligned} \tag{37}$$

where ρ_{t} is the total input offered traffic, $\rho_{\text{t}} \triangleq \rho_{\text{c}} + \rho_{\text{o}} = (\lambda + \lambda_{\text{h}}) E[t_{\text{H}}]$, and β is the *time congestion* which is related as shown below to the *call congestion* [4], that is GOS_1 defined in (25):

$$\text{GOS}_1 = \beta\left[1 + \frac{K}{\rho_{\text{t}}}(z_{\text{t-in}} - 1)\right]. \tag{38}$$

Since GOS_1 is the blocking probability experienced by the total input traffic to a given cell, on the basis of [13], GOS_1 can be approximated as follows:

$$\text{GOS}_1 \approx \text{Erl}\left(\frac{\rho_{\text{t}}}{z_{\text{t-in}}}, \frac{K}{z_{\text{t-in}}}\right), \tag{39}$$

where $\text{Erl}(\gamma, \varepsilon)$ is the extension of the ERLANG-B formula to the case of a non-integral number of servers (γ: offered input traffic, ε: number of servers) which can be obtained by analytic continuation as follows [21]:

$$\text{Erl}(\gamma, \varepsilon) = \frac{1}{\gamma \int_0^\infty \mathrm{e}^{-\gamma y}(1 + y)^{\varepsilon}\, \mathrm{d}y}. \tag{40}$$

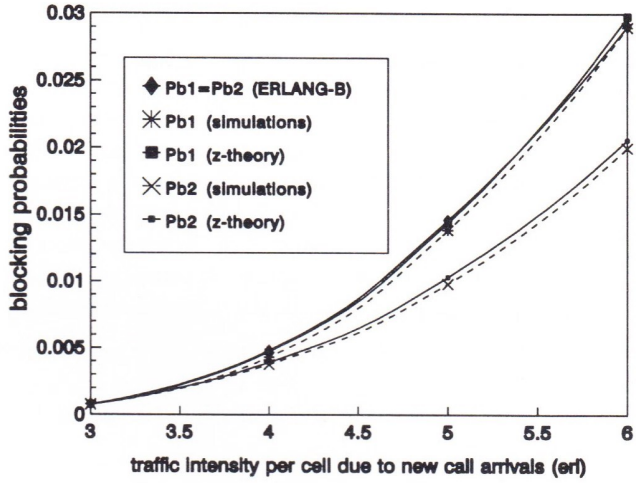

Figure 12. Comparison in the FCA case between simulation results and analytical predictions obtained by means of the new peakedness approach ("z-theory") and the ERLANG-B method.

Equation (39) overestimates the blocking for a smooth traffic, as shown in [13]. A further justification of (34)–(40) is beyond the scope of this paper. The interested reader can refer to [4,13,21,29] for more details. Despite the approximations of this analysis, we will show that it predicts the system performance with a good accuracy within the traffic range which allows reasonable blocking probability values (even more stringent constraints have to be considered in order to fulfill the ITU-T requirements specified in section 2).

Equations (34)–(39) with the related definitions of $E[t_{\text{H}}]$, P_{H}, $\text{Erl}(\gamma, \varepsilon)$ and the flow balance condition (21) form a nonlinear system that, through some algebraic manipulations, can be reduced to three equations in three unknown variables n_{h}, P_{b1} and P_{b2}. This system has been numerically solved with the Gauss–Newton recursive method and the following starting point: $P_{\text{b1}} = 0$, $P_{\text{b2}} = 0$, $n_{\text{h}} = P_{\text{H}}/(1 - P_{\text{H}})$.

In figure 12 simulation results and analytical predictions are compared in the case of the FCA scheme with 10 channels per cell and IRIDIUM-like mobility conditions (i.e., $\alpha = 0.16$). This figure shows that the new analytical approach based on the peakedness factor attains an estimate of both P_{b1} and P_{b2} (i.e., curves denoted by "z-theory") that is in good agreement with simulation results (i.e., dashed curves denoted by "simulations"). As expected, this new analysis gives $P_{\text{b2}} < P_{\text{b1}}$. Referring to the results shown in figure 12, we have theoretically estimated that the value of z_{h} for the handover process is almost equal to 1 for 3 erl/cell and it decreases to about 0.8 for 6 erl/cell.

Figure 12 also presents the analytical predictions derived by assuming a Poisson handover arrival process (i.e., ERLANG-B approach [7,11]). These results can be ob-

tained from the previous formulas (34)–(39) by assuming $z_h \equiv 1$ and, hence, $z_{t\text{-in}} \equiv 1$ (i.e., all input processes are Poisson). Consequently, $P_{b1} \equiv P_{b2}$ is obtained by the classical ERLANG-B formula. In figure 12 we have denoted as "ERLANG-B" the $P_{b1} \equiv P_{b2}$ curve so obtained. This curve drastically overestimated the values of P_{b2} obtained by simulations. Therefore, the ERLANG-B method is inadequate to capture the real nature of the handover process, whereas the peakedness factor approach permits a significant improvement for the theoretical evaluation of blocking probabilities.

8. Conclusions

This paper has investigated the user mobility in LEO-MSSs. Suitable statistical parameters have been defined and analytically characterized under the assumption of a generic convex shape cell. Moreover, a specific LEO-MSS mobility model has been assumed for numerical evaluations. However, the results presented here are quite general and can be easily extended to different mobility models.

We have shown that the blocking performance of a given channel allocation technique becomes worse as user mobility increases. For instance, if the number of handover requests per call doubles, a capacity decrease of about 13% is experienced with FCA-QH in LEO-MSSs in order to fulfill ITU-T requirements with a given number of channels.

Moreover, we have shown that the smooth characteristics of the handover traffic offered to a cell entail a handover failure probability lower than the new call blocking probability. A performance analysis has been carried out which has taken into consideration the peculiarities of the handover arrival process. This new theoretical approach has allowed a good agreement with simulations results.

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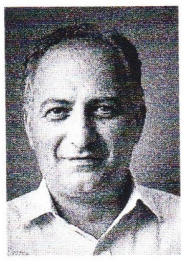

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