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Characterization of user mobility in Low Earth Orbit mobile satellite systems *

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Future mobile communication networks will provide a global coverage by means of constellations with nongeosynchronous satellites. Multi-spot-beam antennas on satellites will allow a cellular coverage all over the Earth. Due to the unstationarity of satellites a call may require many cell changes during its lifetime. These passages will be managed by inter-beam handover procedures. This paper deals with the modeling of the user cell change process during call lifetime in Low Earth Orbit-Mobile Satellite Systems (LEO-MSSs). The analytical derivations presented in this study can be also applied to different mobility models provided that basic assumptions are fulfilled. This paper evaluates the impact of user mobility on the blocking performance of channel allocation techniques. Moreover, the handover arrival process towards a cell has been characterized by using a usual statistical parameter for stationary point processes. Finally, a performance analysis has been carried out on the basis of the classic teletraffic theory for telephone systems.

1. Introduction

Future mobile communication systems are being standardized by the International Telecommunication Union (ITU) under the framework of the International Mobile Telecommunications after the year 2000 (IMT-2000) [19]. The corresponding European activities are carried out by the European Telecommunications Standards Institute (ETSI) under the name Universal Mobile Telecommunications System (UMTS) [1]. An essential feature of IMT-2000 will be the integration of terrestrial cellular networks and Mobile Satellite Systems (MSSs) in order to provide global roaming [5,6].

MSSs permit the extension of mobile communications to scarcely populated areas where a terrestrial system would be unfeasible or too expensive and they can also manage overflow traffic from congested terrestrial cellular networks [6]. The satellite component of IMT-2000 will be (partly or totally) based on nongeostationary satellites, because they guarantee low propagation attenuations and low transmission delays. A particularly attractive solution is given by Low Earth Orbit (LEO) satellites [24] at altitudes from 500 to 2,000 km. Lower altitudes cannot be used, since the atmospheric drag reduces orbit stability; whereas, higher altitudes must be avoided because to cross the Van Allen Belts is harmful for the electronics on board.

Presently, many LEO-MSSs are implemented and deployed [26,27]. Each satellite irradiates on the earth a group of cells with a multi-spot-beam antenna. We consider that cells are fixed with respect to the satellite [31] (figure 1): since the sub-satellite point moves with a speed on the order of 20,000 km/h, a user with a call in progress will cross several cells. A handover procedure manages the transfer of a call from a cell towards an adjacent one. Therefore, it is essential to model the relative satellite-user motion and to evaluate its impact on the performance of channel allocation techniques.

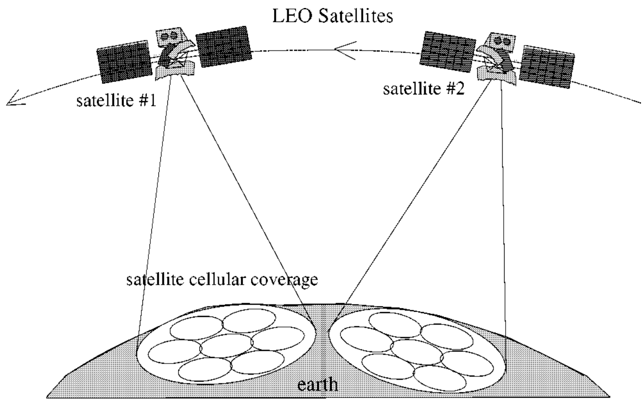

Figure 1. A LEO-MSS with satellite-fixed cells.

Several user mobility models have been proposed in the literature. Some of them are valid for specific scenarios (e.g., terrestrial microcells, linear cellular networks for highways, MSSs) [7,8,17], others have special assumptions for an easy analysis [16,39–41] or are based on general hypotheses [37]. In this paper we propose a mobility model for LEO-MSSs and we carry out simulations to study the impact of different mobility conditions on the performance of resource management strategies. Finally, we characterize the handover arrival process towards a cell and we develop a performance analysis.

2. Quality of Service parameters

Calls that arrive in a cell may be classified as new call arrivals and handed-over calls from adjacent cells. Handed-over calls are produced by the relative satellite-user motion. Let us refer to circuit switched services (i.e., the telephone service). Available channels are assigned to calls, accord-

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ing to a suitable channel allocation algorithm [34]. A call occurring in a cell, where all channels are busy, is blocked and lost (i.e., Blocked Calls are Cleared – BCC). From the resource management standpoint, the main Quality of Service (QoS) parameters are [20]:

- $P_{\rm b1}$, the blocking probability of new call attempts,
- $P_{\rm b2}$, the handover failure probability due to a lack of available resources in the destination cell of the mobile user,
- $P_{\rm drop}$, the call dropping probability due to an unsuccessful handover.

Probabilities $P_{\rm drop}$ and $P_{\rm b1}$ are related to events that directly affect the QoS perceived by users. Since call dropping is more undesirable from the user standpoint than the initial blocking of a new call attempt, $P_{\rm drop}$ needs a stronger requirement than $P_{\rm b1}$. The target values for the QoS parameters have been specified by ITU-T [20]: $P_{\rm drop}$ and $P_{\rm b1}$ should not exceed $5 \cdot 10^{-4}$ and 10^{-2}, respectively. If the user mobility increases (i.e., the average number of handover procedures during call lifetime increases) it becomes critical to keep $P_{\rm drop}$ below $5 \cdot 10^{-4}$. Hence, suitable handover management strategies must be used to prioritize the service of handover requests with respect to the service of new call attempts. These strategies can be compared and selected only on the basis of suitable mobility models. The unavoidable drawback of any handover prioritization technique is the increase in the blocking probability for new call attempts [7,34] and, hence, the reduction in the amount of traffic admitted in the network. A good trade-off between user's needs (i.e., the QoS) and operator's needs (e.g., the traffic quantity managed by the network) has to be considered.

3. User mobility in LEO-MSSs

A mobility model contains a set of rules that permit one to predict statistically how long a call will hold a channel in a cell and if/when this call will originate a handover request towards an adjacent cell. The following aspects characterize the user mobility and the handover generation process towards a cell:

- the handover algorithm and its parameters (e.g., thresholds, hysteresis margin [28]),
- the signal propagation conditions in the radio channel,
- the type of cellular coverage,
- the user speed and direction,
- the traffic distribution in the territory,
- the statistical characteristics of the call duration time.

These aspects depend on the scenario considered (e.g., terrestrial cellular system in urban area, LEO-MSS with global coverage). The handover algorithm, the signal propagation conditions, and the cellular layout determine the shape and the size of the cells and, then, their borders. In this work we assume that cells have a well-defined geometry (i.e., deterministic borders). Moreover, we consider the following basic assumptions in order to study user mobility:

- the traffic is uniformly distributed all over the network;
- users move in straight lines within a cell;
- motion rules allow a uniform distribution of users all over the cellular network;
- the unencumbered call duration time, $t_{\rm d}$, is exponentially distributed[1];
- all the cells have the same shape and size;
- cells are convex: for a mobile user which crosses a cell following a straight line, there is a unique entry point and a unique exit point;
- new calls occur in the cells according to cell-to-cell independent Poisson processes.

These hypotheses allow *homogeneous conditions* for the handover traffic all over the cells of the network. Under these assumptions, different mobility models can be defined depending on the cell size, the cell shape and the characteristics of the mobile user velocity vector (e.g., see the mobility models in [8,10,16,17,36,37,39]). Once these aspects are defined, it is possible to analyze the different statistical parameters of a mobility model that are defined in table 1. In what follows, we will denote by *source cell* the cell where the call starts and by *transit cell* any subsequent cell reached by the mobile user with the call in progress.

In order to characterize the user mobility in LEO-MSSs we have added the two following conditions to the previous general assumptions:

- a satellite-fixed-cell system is envisaged [31];
- due to the high value of the satellite ground-track speed, $V_{\rm trk}$ (e.g., $V_{\rm trk} \approx 26{,}000$ km/h, for LEO satellites placed at an altitude of about 700 km), with respect to the other motion component speeds (i.e., the Earth rotation around its axis and the user motion relative to the Earth), any user moves relatively to the satellite antenna footprints on the Earth with a speed equal to $V_{\rm trk}$ [7,9,10,14].

According to the above assumptions, it follows that mobile users cross the cells following parallel straight trajectories. The statistical parameters defined in table 1 and in section 2 (e.g., $P_{\rm drop}$, $P_{\rm Hi}$, $n_{\rm h0}$) will be analytically characterized in the next section, where we will also discuss the possibility to extend our results to other mobility models proposed in the literature [7,16,37,38].

[1] Owing to the memoryless property of the exponential distribution, the residual time duration of a call after a handover has the same distribution of the unencumbered call duration; therefore, we will still denote by $t_{\rm d}$ the residual call lifetime after a handover request.

Table 1
The parameters that characterize a mobility model.

Parameter	Definition
α	A dimensionless parameter that characterizes the degree of user mobility; it is given by the ratio between the *cell radius* and the average distance covered by a mobile user during call lifetime.
t_d	The unencumbered call duration with an exponential distribution and mean value T_m.
t_{mci}	The random variable that represents the time required by a mobile user to cross *a given cell* (according to a given trajectory) from the origination point of the call in this cell to the border ($i = 1$) or from border to border ($i = 2$) (figure 2).
t_{Hi}	The random variable that represents the channel holding time in *a given cell* for a call originated in this cell ($i = 1$) or coming from an adjacent cell ($i = 2$).
P_{Hi}	The probability that a call served in *a given cell* (this cell is: the source of the call for $i = 1$; a transit cell of the call for $i = 2$) requires a handover towards an adjacent cell.
n_h	The average number of handover requests per call.
n_{h0}	The average number of handover requests per call in absence of blocking (i.e., $P_{b1} = P_{b2} = 0$).
t_{wmax}	The time spent by a user to cross the overlap area between adjacent cells.
S	A dimensionless coefficient obtained as the ratio between the average time spent by a mobile user in the overlap area among adjacent cells (i.e., $E[t_{wmax}]$) and the average mobile sojourn time in a cell (i.e., $E[t_{mc2}]$).
λ	The mean arrival rate of new call attempts per cell (uniform traffic case).
λ_h	The mean arrival rate of handover requests per cell (uniform traffic case).

4. Derivation of main system parameters

This section deals with analytical derivations of the statistical parameters of the LEO mobility model.

4.1. Basic parameters

On the basis of the definitions given in table 1, parameters α and S are respectively obtained as

$$\alpha \triangleq \frac{R}{E[\nu]T_m}, \qquad S \triangleq \frac{E[t_{wmax}]}{E[t_{mc2}]}, \tag{1}$$

where

- T_m is the average call duration;
- $E[\nu]$ is equal to V_{trk}, according to the LEO mobility assumptions;
- R is one half the maximum cell diameter, for a generic cell shape.

In LEO-MSSs, 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.

Parameter α is positive and dimensionless. We will show later that parameter α is related to the mobility degree: low values of α entail frequent handover requests during call lifetime. The degree of coverage overlap among adjacent cells is measured by the dimensionless parameter S, which ranges from 0 to 1. Future microcellular systems will be characterized by a high degree of both mobility and overlap: values of α less than 1 and values of S close to 0.5 are expected [30,35].

4.2. The distribution of the crossed distance in a cell

Let x_1 denote the distance crossed in a given cell y by a user from the new call arrival instant in it and let x_2 denote the distance covered by a user from border to border in a given cell y. Once a specific cell shape is identified, we obtain the probability density functions $f_{x_1}(d)$, $f_{x_2}(d)$

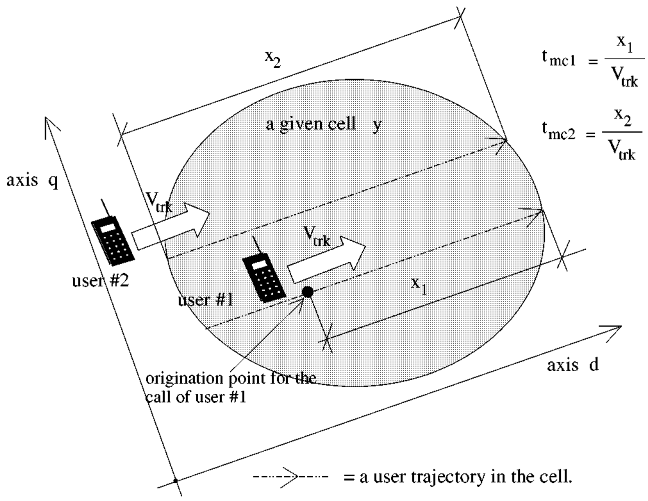

Figure 2. Description of the crossed distance in cell y from the call arrival instant in y for a user that originates a call in this cell (user #1) and for a user with a handed-over call to cell y (user #2).

respectively of x_1, x_2, by taking into account that, in our model, users cross the cells following straight and parallel lines.

Let us consider a reference for a given cell y (figure 2), where an axis is parallel (axis d) and the other axis is orthogonal (axis q) to the user motion direction. In order to derive $f_{x_1}(d)$ and $f_{x_2}(d)$ we consider that a user crosses cell y for a given value of the offset $q \in [q_{min}, q_{max}]$. It follows that the user trajectory intercepts a segment with length $h(q)$ in y. We have the two following cases: (i) a user with a new call attempt on this segment crosses a distance x_1 in the cell from the call arrival instant which has a probability density function (pdf) uniformly distributed from 0 to $h(q)$; (ii) a user with a handed-over call in cell y crosses a distance from the call arrival instant equal to $h(q)$. In both cases, we remove the conditioning on offset q. Due to the uniform traffic assumption, the probability that a new call attempt occurs in cell y on the elementary area with length $h(q)$ and height dq is equal to $h(q)\,\mathrm{d}q/A$, where A

is the cell area, while a handed-over call towards cell y crosses this cell with an offset which is uniformly distributed[2] from $q_{\min}$ to $q_{\max}$ [11]. In conclusion, $f_{x_1}(d)$ and $f_{x_2}(d)$ are

$$f_{x_1}(d) = \int_{q_{\min}}^{q_{\max}} \left[\frac{u(d) - u(d-h(q))}{h(q)}\right] \frac{h(q)}{A}\,\mathrm{d}q,$$
$$f_{x_2}(d) = \frac{1}{q_{\max} - q_{\min}} \int_{q_{\min}}^{q_{\max}} \delta\big(d - h(q)\big)\,\mathrm{d}q, \tag{2}$$

where $u(x)$ is the unit step function: $u(x) = 1$ for $x \geqslant 0$; $u(x) = 0$ otherwise; $\delta(x)$ is the Dirac delta function.

It is straightforward to verify that the expressions of $f_{x_1}(d)$ and $f_{x_2}(d)$ given in (2) fulfill the following relationship:

$$f_{x_1}(d) = \frac{1 - F_{x_2}(d)}{E[x_2]}, \tag{3}$$

where $F_{x_2}(d)$ is the Probability Distribution Function (PDF) of variable x_2.

From (2) we obtain $E[x_1]$ and $E[x_2]$ as follows:

$$E[x_1] = \frac{1}{2A}\int_{q_{\min}}^{q_{\max}} h^2(q)\,\mathrm{d}q, \qquad E[x_2] = \frac{A}{q_{\max} - q_{\min}}. \tag{4}$$

Equations (2)–(4) can be used, for instance, in the model proposed in [37], since the basic assumptions shown in section 3 are fulfilled.

4.3. The excess life theorem

Let us consider a given cell y (figure 2); t_{mc2} is the time spent by a mobile user to cross cell y from border to border (i.e., the mobile sojourn time in a cell), whereas t_{mc1} is the time spent in cell y by a user from the new call arrival instant. According to the definitions of distances x_1 and x_2, we have

$$t_{\mathrm{mc1}} = \frac{x_1}{V_{\mathrm{trk}}}, \qquad t_{\mathrm{mc2}} = \frac{x_2}{V_{\mathrm{trk}}}. \tag{5}$$

Under the assumptions made in section 3, $f_{x_1}(d)$ and $F_{x_2}(d)$ are related by (3). We obtain below a similar formula which relates the distributions of variables t_{mc1} and t_{mc2}. According to (5), the pdfs of t_{mc1} and t_{mc2} are obtained as

$$f_{t_{\mathrm{mc1}}}(t) = V_{\mathrm{trk}} f_{x_1}(tV_{\mathrm{trk}}), \tag{6}$$
$$f_{t_{\mathrm{mc2}}}(t) = V_{\mathrm{trk}} f_{x_2}(tV_{\mathrm{trk}}). \tag{7}$$

If we substitute (3) in (6) and we use (7) to obtain the PDF of t_{mc2}, after performing some algebraic manipulations we have

$$f_{t_{\mathrm{mc1}}}(t) = \frac{1 - F_{t_{\mathrm{mc2}}}(t)}{E[t_{\mathrm{mc2}}]}, \tag{8.a}$$

[2] Under the homogeneous conditions shown in section 3, all parallel trajectories are equally likely, for a transit cell.

or equivalently, by using the Laplace transforms of the distributions,

$$T_{\mathrm{mc1}}(s) = \frac{1 - T_{\mathrm{mc2}}(s)}{sE[t_{\mathrm{mc2}}]}, \tag{8.b}$$

where $T_{\mathrm{mc}i}(s) = \mathcal{L}[f_{\mathrm{tmc}i}(t)]$ is the Laplace transform of the pdf of variable $t_{\mathrm{mc}i}$ $(i = 1, 2)$, $F_{\mathrm{tmc}i}(t)$ is the PDF of variable $t_{\mathrm{mc}i}$ $(i = 1, 2)$.

Equation (8) means that t_{mc1} can be considered as a residual time in the interval t_{mc2} with respect to a generic arrival instant within t_{mc2} (*excess life theorem* [32]).

On the basis of (5), we have

$$E[t_{\mathrm{mc1}}] = \frac{E[x_1]}{V_{\mathrm{trk}}}, \qquad E[t_{\mathrm{mc2}}] = \frac{E[x_2]}{V_{\mathrm{trk}}}. \tag{9}$$

The study made in this section can be easily extended to other mobility models found in the literature. In particular, we can use (8) also if the user speed in a cell is a random variable with known distribution [16,37,38]. In this case, the users with handed-over calls have a speed which follows a biased sampling distribution [36]; moreover, $f_{\mathrm{tmc}i}(t)$ must be related to $f_{x_1}(d)$ as shown in [17].

In [32,39,40], the excess life theorem has been applied to relate the distribution of the time spent in a transit cell to that of the time spent in the source cell (from the call origination instant) for a given call, in cases where mobility conditions are both homogeneous and memoryless (i.e., the sojourn times of a mobile user in subsequent cells are *independent identically distributed*, iid). The considerations made in this section permit applying the excess life theorem without requiring the memoryless assumption[3] to relate the distributions of times spent in a given cell y by mobile users. Note that iid mobile sojourn times in subsequent cells are possible in LEO-MSSs if a mobile user crosses a fixed distance in subsequent cells (i.e., square shaped cells crossed according to parallel trajectories with respect to cell sides). In section 5 we will present simulation results for this case.

4.4. Handover probabilities

A call originated in cell y generates a handover request if $t_{\mathrm{d}} > t_{\mathrm{mc1}}$, whereas a handed-over call served in cell y generates a further handover request if $t_{\mathrm{d}} > t_{\mathrm{mc2}}$. The probabilities of these events are P_{H1} and P_{H2} defined in table 1. Under the sole (general) assumption of t_{d} exponentially distributed, we have

$$\begin{aligned} P_{\mathrm{H}i} &\triangleq \Pr\{t_{\mathrm{d}} > t_{\mathrm{mc}i}\} \\ &= \int_0^{+\infty} \Pr\{t_{\mathrm{d}} > t \mid t_{\mathrm{mc}i} = t\} f_{t_{\mathrm{mc}i}}(t)\,\mathrm{d}t \\ &= \int_0^{+\infty} \mathrm{e}^{-t/T_{\mathrm{m}}} f_{t_{\mathrm{mc}i}}(t)\,\mathrm{d}t \end{aligned}$$

[3] The assumptions made in section 3 lead to a *geometric mobility model* where there is memory for the motion of a user from cell to cell: the sojourn time spent in a cell depends on the sojourn times spent in previous cells.

$$= T_{mci}\left(s = \frac{1}{T_m}\right), \quad \text{where}$$
$$i = \begin{cases} 1 & \text{for new calls in } y, \\ 2 & \text{for handed-over calls to } y, \end{cases} \quad (10)$$

where $T_{mci}(s)$ denotes the Laplace transform of $f_{tmci}(t)$, which can be computed according to what is shown in the previous subsection.

We expect that $P_{H2} < P_{H1}$, since, on average, the time spent to cross a cell from border to border is greater than the time spent to reach the border from an internal point of the cell. This interesting characteristic will be confirmed by the numerical examples presented in section 5.

Finally, it is interesting to remark that (10) being obtained under the sole assumption of exponentially distributed call duration time, it can be directly applied to different mobility models (e.g., those described in [7,8,16,17,39]).

4.5. Channel holding time

A new call holds a channel in cell y for a time t_{H1}, whereas a handed-over call uses a channel in y for a time t_{H2}. The channel holding time in a cell, t_{Hi} $(i = 1, 2)$, is linked to t_{mci} as follows [17]:

$$t_{Hi} \triangleq \min[t_d, t_{mci}], \quad \text{where}$$
$$i = \begin{cases} 1 & \text{for new calls in } y, \\ 2 & \text{for handed-over calls to } y. \end{cases} \quad (11)$$

The pdfs for variables t_{Hi} can be found from those of variables t_d and t_{mci} as shown below:

$$f_{t_{Hi}}(t) = f_{t_d}(t)\left[1 - F_{t_{mci}}(t)\right] + f_{t_{mci}}(t)\left[1 - F_{t_d}(t)\right]. \quad (12)$$

Let us consider the pdf of t_{Hi} conditioned on $t_{mci} = \tau$. On the basis of (12) and under the sole assumption of t_d exponentially distributed with expected value T_m, we have

$$f_{t_{Hi}|t_{mci}=\tau}(t) = e^{-t/T_m} \frac{[u(t) - u(t-\tau) + T_m\delta(t-\tau)]}{T_m}. \quad (13)$$

From (13) we obtain the expected value of t_{Hi} conditioned on $t_{mci} = \tau$:

$$E[t_{Hi} \mid t_{mci} = \tau] = \int_0^{+\infty} t f_{t_{Hi}|t_{mci}=\tau}(t)\,dt$$
$$= T_m\left[1 - e^{-\tau/T_m}\right]. \quad (14)$$

We remove in (14) the conditioning on t_{mci} as follows:

$$E[t_{Hi}] = \int_0^{+\infty} E[t_{Hi} \mid t_{mci} = \tau] f_{t_{mci}}(\tau)\,d\tau$$
$$= T_m[1 - P_{Hi}]. \quad (15)$$

Also this result can be extended to different mobility models [7,8,16,17,39]. Equation (15) analytically expresses an intuitive concept: on average, the channel holding time is reduced with respect to the unencumbered call duration owing to user motion. Moreover, since we expect that $P_{H2} < P_{H1}$, therefore $E[t_{H2}] > E[t_{H1}]$.

4.6. Average number of handover requests per call in absence of blocking

We consider $P_{b1} = P_{b2} = 0$ (i.e., an ideal system with such large resources that no channel demand is blocked) and we evaluate the average number of handover requests per call, n_{h0}. Nanda in [25] assumes arbitrary call duration distributions and stationary cell sojourn time distributions (i.e., the cell change process is a stationary point process) and proves that n_{h0} is given by

$$n_{h0} = \frac{T_m}{E[t_{mc2}]} \frac{\text{handovers}}{\text{call}}. \quad (16)$$

If we compare (16) with (8.b) computed in $s = 1/T_m$, we have that $T_m/E[t_{mc2}]$ equals $P_{H1}/(1 - P_{H2})$. Therefore,

$$n_{h0} = \frac{P_{H1}}{1 - P_{H2}} \frac{\text{handovers}}{\text{call}}. \quad (17)$$

This result can be easily verified in the case that the sojourn times of a user in subsequent cells are iid random variables [25,39,40]. This assumption entails both a homogeneous cellular system and a memoryless generation process for handover requests during call lifetime. In these particular conditions, P_{H1} is the handover probability from the source cell of the call and P_{H2} is the handover probability from each transit cell. Hence, the number of handover requests during call lifetime is modeled by a geometric distribution based on probabilities P_{H1} and P_{H2}, as shown in table 2. Consequently, the average number of handover requests per call in absence of blocking, n_{h0}, is

$$n_{h0} = \sum_{k=1}^{\infty} k P_{H1} P_{H2}^{k-1}(1 - P_{H2})$$
$$= \frac{P_{H1}}{1 - P_{H2}} \frac{\text{handovers}}{\text{call}}. \quad (18)$$

This result is consistent with (17), which has been derived under more general assumptions.

On the basis of parameter n_{h0} we can evaluate the impact of the cell shape on the mobility in LEO-MSSs. In particular, let us consider hexagonal cells with side R_1 and square cells with side R_2. In both cases, we assume that user trajectories are orthogonal with respect to a cell side. According to (16), n_{h0} depends on $E[t_{mc2}]$, which is given by (9), where $E[x_2]$ is obtained from (4); $E[x_2]$ depends on both the cell shape and user trajectory orientation with

Table 2
The distribution for the number of handover requests per call, when $P_{b1} = P_{b2} = 0$.

Number of handover requests per call in the absence of blocking	Probability
0	$1 - P_{H1}$
1	$P_{H1}(1 - P_{H2})$
2	$P_{H1}P_{H2}(1 - P_{H2})$
⋮	⋮
k	$P_{H1}P_{H2}^{k-1}(1 - P_{H2})$

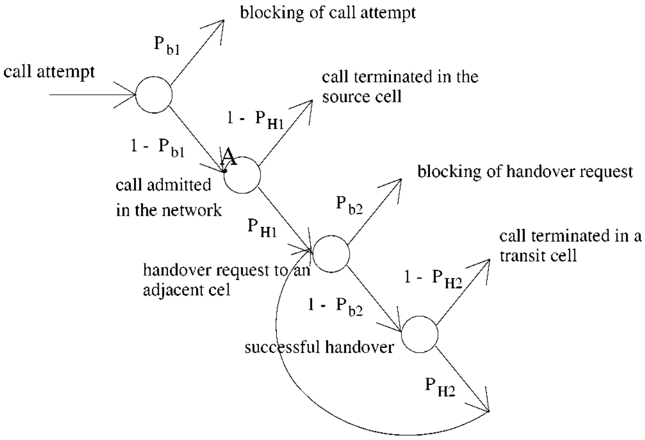

Figure 3. The handover generation process during call lifetime in the case that mobile sojourn times in subsequent cells are iid random variables.

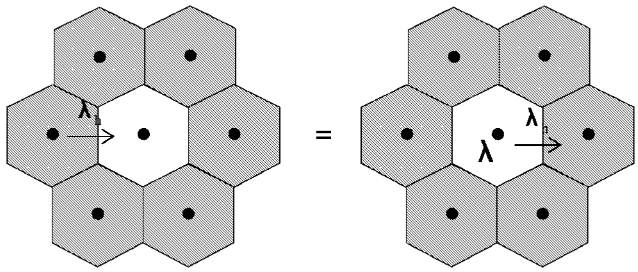

Figure 4. The equilibrium between calls that enter a cell and calls that go out from a cell.

respect to the cell. In our case we have $E[x_2] = 3\sqrt{3}R_1/4$, for hexagonal cells, and $E[x_2] = R_2$, for square cells. Finally, the following results are obtained for n_{h0}:

$$n_{h0} = \begin{cases} \dfrac{T_m V_{trk}}{R_1}\dfrac{4}{3\sqrt{3}} & \text{for hexagonal cells,} \\ \dfrac{T_m V_{trk}}{R_2} & \text{for square cells} \end{cases} \tag{19}$$

(handovers/call). If we assume equal areas for both cell shapes (this is true if $R_2 = \sqrt{3\sqrt{3}/2R_1}$), the hexagonal cell entails a 24% increase in the number of handover requests per call with respect to the square cell.

4.7. Average number of handover requests per call in the presence of blocking

Let us assume iid mobile sojourn times in subsequent cells and a homogeneous system (see section 3). In this case, the handover generation process during call lifetime is memoryless. Figure 3 shows the handover generation diagram for a call in the presence of blocking (i.e., $P_{b1} > 0$ and $P_{b2} > 0$). The distribution of the number of handover requests per call attempt is obtained as explained below.

- A call does not generate handover requests provided that either it is initially blocked or it ends in its source cell. This occurs with probability

$$Q_0 = P_{b1} + (1 - P_{b1})(1 - P_{H1}) = 1 - P_{H1}(1 - P_{b1}).$$

- A call generates one handover request if it is not initially blocked, and if only one handover is required (i.e., either this handover is unsuccessful or the call terminates in the first transit cell). This occurs with probability

$$\begin{aligned} Q_1 &= (1 - P_{b1})P_{H1}\big[P_{b2} + (1 - P_{b2})(1 - P_{H2})\big] \\ &= (1 - P_{b1})P_{H1}\big[1 - P_{H2}(1 - P_{b2})\big]. \end{aligned}$$

- A call generates k handover requests (with $k \geqslant 1$) if it is not initially blocked, if $k-1$ handovers are successfully accomplished, if a further handover is requested and if no other handover is performed. This occurs with probability

$$\begin{aligned} Q_k &= (1 - P_{b1})P_{H1}(1 - P_{b2})\big[P_{H2}(1 - P_{b2})\big]^{k-2} \\ &\quad \times P_{H2}\big[P_{b2} + (1 - P_{b2})(1 - P_{H2})\big] \\ &= (1 - P_{b1})P_{H1}\big[P_{H2}(1 - P_{b2})\big]^{k-1} \\ &\quad \times \big[1 - P_{H2}(1 - P_{b2})\big]. \end{aligned}$$

On the basis of the distribution Q_k we obtain the average number of handover requests per call attempt, n_h, as follows:

$$\begin{aligned} n_h &= \sum_{k=1}^{\infty} kQ_k \\ &= \frac{P_{H1}(1 - P_{b1})}{1 - (1 - P_{b2})P_{H2}}\ \frac{\text{handover requests}}{\text{call attempt}}. \end{aligned} \tag{20}$$

It is straightforward to verify that by setting $P_{b1} = P_{b2} = 0$ in (20) we obtain (18). The effect of the blocking (i.e., $P_{b1} > 0$ and $P_{b2} > 0$) is that the average number of handover requests per call, n_h, decreases with respect to n_{h0}.

If we remove the assumption of iid mobile sojourn times in subsequent cells, we must evaluate n_h conditioned on a given mobile user trajectory and then remove the conditioning by using the trajectory probability distribution[4].

4.8. Relationship between the average handover rate and the average new call arrival rate for a cell

According to the basic assumptions made in section 3, we have a uniform traffic: λ denotes the average arrival rate for new call attempts in a given cell y, whereas λ_h is the mean arrival rate for handed-over calls in cell y. We consider that an equilibrium exists (figure 4), in any time interval, between the average number of calls that enter cell y and the average number of calls that leave cell y towards adjacent cells (*flow conservation*) [7,8]. The mean handover rate due to calls which leave a given cell y is obtained as the sum of the two following contributions:

- $\lambda(1 - P_{b1})P_{H1}$, which represents the mean rate of calls originated in cell y that leave cell y towards an adjacent cell;

[4] Under the assumptions made in section 3, all user trajectories are parallel and equally likely.

- $\lambda_h(1 - P_{b2})P_{H2}$, which represents the mean rate of calls arrived in cell y by handovers that leave cell y towards an adjacent cell.

The equilibrium condition requires that the sum of these two contributions is equal to the mean rate of handed-over calls towards cell y, that is λ_h. Hence, we have

$$\lambda_h(1 - P_{b2})P_{H2} + \lambda(1 - P_{b1})P_{H1} = \lambda_h. \tag{21}$$

From (21), we obtain λ_h/λ as

$$\frac{\lambda_h}{\lambda} = \frac{(1 - P_{b1})P_{H1}}{1 - (1 - P_{b2})P_{H2}}. \tag{22}$$

According to (22), the average rate of handover requests towards a cell, λ_h, depends on both the mean rate of new call attempts, λ, the handover probabilities P_{H1} and P_{H2}, and the blocking probabilities P_{b1} and P_{b2}. This entails a feedback in the loss queuing system used to model the behavior of a generic cell with the BCC policy: the blocking probabilities P_{b1} and P_{b2} depend on the total arrival process in a cell (i.e., handover requests plus new call attempts) and this arrival process depends, in turn, on the blocking probabilities. Hence, analytical derivations of the blocking probabilities need a recursive approach [7,8,11,39]. An example is shown in section 7.

If we make the additional assumption of iid mobile sojourn times in subsequent cells, from (20) and (22) we obtain the following relationship between n_h and λ_h/λ:

$$n_h = \frac{\lambda_h}{\lambda}. \tag{23}$$

Equation (23) represents a sort of *ergodicity condition* for the handover generation process: on the left side we have a parameter related to a generic call that is equal on the right side to a quantity related to a generic cell. This formula must not surprise, since it has been derived under the assumption of a homogeneous system and memoryless mobility conditions (i.e., all the cells have the same traffic, the same shape and size, the same mobility characteristics).

If we remove the assumption of iid mobile sojourn times in subsequent cells, we can still use (23) as a first approximation. It is important to note that there is a case where (23) is exact even if mobile sojourn times in subsequent cells are not independent: $P_{b1} = P_{b2} = 0$ (in such a case (17) and (22) become equal).

4.9. Call dropping probability

We consider the basic assumptions made in section 3 and the additional assumption of iid mobile sojourn times in subsequent cells. To study the call dropping event, the handover diagram shown in figure 3 must be considered starting from point A (i.e., a call accepted into the network). A call in progress is dropped at the kth handover request if the two following independent events occur [7]:

- a call lasts so as to produce at least k handover requests ($k = 1, 2, \ldots$); this occurs with probability $P_{H1}P_{H2}^{k-1}$;
- a call accepted into the system is dropped with probability $P_{b2}(1 - P_{b2})^{k-1}$ at the kth handover.

The call dropping probability P_{drop} is obtained as the sum of the probabilities that a call is dropped at the kth handover for k from 1 to infinity:

$$P_{drop} = \sum_{k=1}^{\infty} P_{H1}P_{H2}^{k-1}P_{b2}(1 - P_{b2})^{k-1} = \frac{P_{H1}P_{b2}}{1 - P_{H2}(1 - P_{b2})}. \tag{24}$$

If we remove the assumption of iid mobile sojourn times in subsequent cells, (24) is not generally applicable. In such a case, we must evaluate P_{drop} conditioned on a given mobile user trajectory and then remove the conditioning by using the trajectory probability distribution.

4.10. Grade Of Service

Several ways are possible to define the *Grade Of Service* (GOS). A first possibility, denoted by GOS_1, is to consider probabilities P_{b1} and P_{b2} weighed by the relative percentages of arrivals:

$$GOS_1 \triangleq \frac{\lambda}{\lambda + \lambda_h}P_{b1} + \frac{\lambda_h}{\lambda + \lambda_h}P_{b2}. \tag{25}$$

Parameter GOS_1 (see also [18,22] for a similar definition) will be used in the theoretical study made in section 7, since GOS_1 is the *call congestion* for the loss queuing system which models a cell with heterogeneous input traffic (due to new call attempts and handover requests). Under the assumption of iid mobile sojourn times in subsequent cells, we can use (23) in (25).

Another GOS definition could be to consider that the dropping of a call is a more frustrating event than the blocking of a new call attempt. Accordingly, we consider GOS_2 as follows:

$$GOS_2 \triangleq P_{b1} + 10P_{drop}. \tag{26}$$

GOS_2 weights P_{drop} 10 times more than P_{b1}: this parameter is not a probability, but may express the QoS perceived by users [17]. Of course, the higher the GOS_2 value the poorer the QoS provided to users. We will use the GOS_2 parameter to evaluate the impact of different user mobility conditions on the performance of a channel allocation scheme.

5. Performance evaluation

In this section, we derive the performance of a LEO-MSS with a specific cell shape. In addition to the assumptions made in section 3, we consider (figure 5):

- The cells (i.e., footprints of the antenna spot-beams from satellites) of the network are disposed on the Earth according to a hexagonal layout and have a square shape (with side $2R$). The use of this cell shape entails simpler

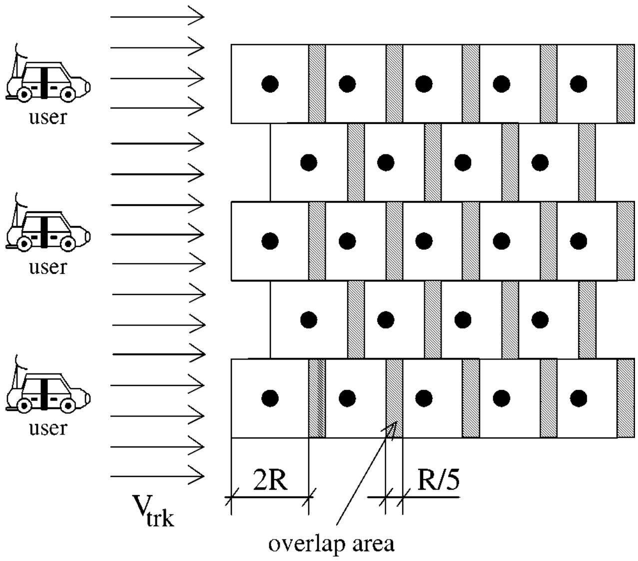

Figure 5. Illustration of the mobility model for LEO-MSSs.

analytical derivations to characterize the user mobility parameters (e.g., P_{H1}, P_{H2}, etc.).

- Mobile users cross the cellular network with a relative velocity V_{trk}, disposed with respect to cell sides, as shown in figure 5. Hence, denoting by $d_{\mathrm{c}}(y)$ the distance crossed in cell y by a mobile user from the arrival instant of its call in cell y (this cell can be either the source cell or a transit one), we have[5]:

  * $d_{\mathrm{c}}(y)$ is uniformly distributed between 0 and $2R$, if cell y is the source cell of the call;
  * $d_{\mathrm{c}}(y)$ is deterministically equal to $2R$, if cell y is a transit cell for the call.

- The time to cross the overlap area, t_{wmax}, has a deterministic value, equal for any handover request, that is obtained according to the following formula:

$$t_{\mathrm{wmax}} = \frac{R}{5V_{\mathrm{trk}}}. \tag{27}$$

  According to (1), S is equal to 0.1 (conservative assumption).

- New calls originated in an overlap area between adjacent cells are immediately addressed to the destination cell in order to avoid that they immediately need to be handed-over.

This model has been adopted in the SAINT project (SATellite INTegration in the Future Mobile Network) [3] within the framework of RACE II, a European Commission financed research program. This is a one-dimensional mobility model that is also suitable for linear cellular networks used for highways and railways. Parameter α is obtained as the ratio between R and $T_{\mathrm{m}}V_{\mathrm{trk}}$. We have the following distributions for t_{mc1} and t_{mc2}:

$$f_{t_{\mathrm{mc1}}}(t) = \frac{V_{\mathrm{trk}}}{2R}\left[u(t) - u\left(t - \frac{2R}{V_{\mathrm{trk}}}\right)\right], \tag{28}$$

$$f_{t_{\mathrm{mc2}}}(t) = \delta\left(t - \frac{2R}{V_{\mathrm{trk}}}\right). \tag{29}$$

These distributions represent a very special case which fulfills the excess life theorem (8). In addition to this, the mobility assumptions guarantee that the mobile sojourn time in a cell does not depend on that of the previous cells, i.e., mobile sojourn times in subsequent cells are iid. Then, the handover generation process is memoryless. The analytical derivations obtained in section 4 can be applied to this mobility case. In particular, on the basis of (10), (28) and (29) we obtain the following expressions for P_{H1} and P_{H2}:

$$P_{\mathrm{H1}}(\alpha) = \frac{1 - \mathrm{e}^{-2\alpha}}{2\alpha}, \qquad P_{\mathrm{H2}}(\alpha) = \mathrm{e}^{-2\alpha}. \tag{30}$$

It is worth noting that P_{H1} and P_{H2} are functions of the mobility parameter α: as α decreases to 0 (or increases to ∞), that is the mobility increases (decreases), both P_{H1} and P_{H2} approach 1 (0). Hence, from (19) and (30), n_{h0} results in

$$n_{\mathrm{h0}} = \frac{1}{2\alpha} \; \frac{\text{handovers}}{\text{call}}. \tag{31}$$

By assuming a fixed value for T_{m}, the user mobility increases (i.e., n_{h0} increases) if V_{trk} increases and/or R decreases. Then, in general, we can consider that the mobility increases if the satellite altitude decreases; correspondingly, the number of satellites of the LEO constellation increases as well [24].

For LEO-MSSs, α values less than unity are expected. In particular, for the IRIDIUM system [7,9,10], we may consider $V_{\mathrm{trk}} = 26{,}600$ km/h and $R = 212.5$ km; then, $\alpha \approx 0.16$ if $T_{\mathrm{m}} = 3$ min. Correspondingly, $P_{\mathrm{H1}} \approx 85\%$ and $P_{\mathrm{H2}} \approx 72\%$. From (31), about 3.125 spot-beam handovers are required, on average, during call lifetime. Finally, on the basis of (27), t_{wmax} is about equal to 0.1 min.

In figure 6, the behaviors of P_{b1}, P_{drop} and GOS_2 have been shown as functions of parameter α. The results given in this figure have been obtained for a Fixed Channel Allocation scheme with the Queuing of the Handovers that cannot be immediately served (FCA-QH) [7,34] by simulating a parallelogram shaped cellular network folded onto itself as shown in [9,10]. Simulations have been carried out under the conditions listed below:

- the average call duration T_{m} is equal to 3 min;
- the maximum queuing time for handover requests t_{wmax} is obtained from (27);
- new call attempts arrive at a cell with a mean rate λ equal to 1.67 calls/min;

[5] The distance $d_{\mathrm{a}}(y)$, crossed by a user in cell y while its call is active (irrespective of y being the source cell or a transit one), is equal to $d_{\mathrm{c}}(y)$, except when y is the termination cell of the call (i.e., the cell where either the call naturally ends or it is dropped at cell boundaries for an unsuccessful handover towards an adjacent cell), because $d_{\mathrm{a}}(y) \leqslant d_{\mathrm{c}}(y)$, if the call naturally ends in cell y. In general we have: $d_{\mathrm{a}}(y) = \min[d_{\mathrm{c}}(y),\ t_{\mathrm{d}}V_{\mathrm{trk}}]$; this formula can be used to obtain the distribution of $d_{\mathrm{a}}(y)$ from those of $d_{\mathrm{c}}(y)$ and t_{d}, by following a similar approach to (12).

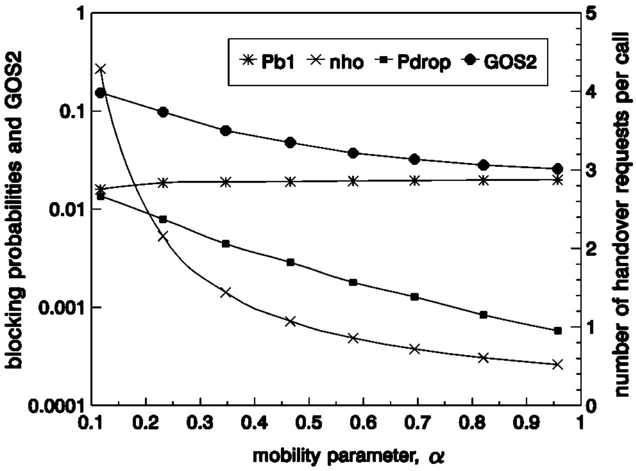

Figure 6. Behaviors of P_{b1}, P_{drop}, GOS_2 and n_{h0} for the FCA-QH technique as functions of parameter α in LEO-MSSs.

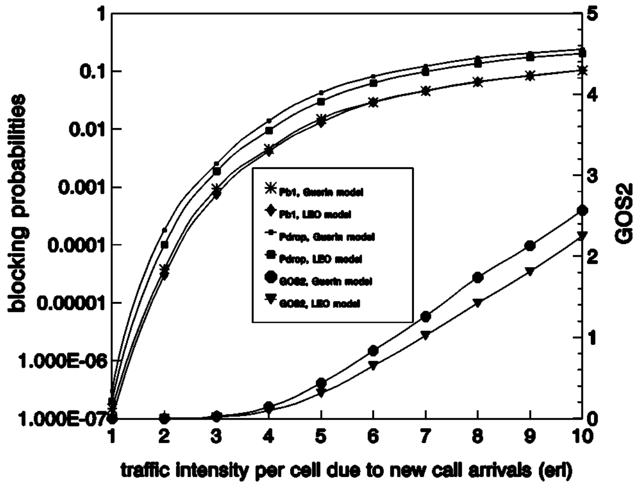

Figure 7. Comparison between the Guérin's mobility model and the LEO one at a parity of n_{h0}, for FCA.

- a cluster of 7 cells is considered [23];
- a parallelogram shaped cellular network folded onto itself with 7 cells per side is used;
- 70 channels are available to the system; then, according to the selected cluster size, each cell has permanently allocated 10 channels;
- a First Input First Output (FIFO) queuing discipline has been considered for handovers which do not immediately obtain service;
- each cell has 10 rooms for queuing handover requests;
- HPBW of the satellite antenna spot-beams has been kept fixed and equal to 0.27 radiants (this value gives a cell radius about equal to 212.5 km for a satellite altitude of 780 km). We have considered that the LEO satellite altitude increases from 500 to 2,000 km; hence, on the basis of HPBW $= 0.27$ radiants and $T_m = 3$ min, α ranges from 0.1 to 0.7, because V_{trk} diminishes [14] and R increases.

In figure 6, we have also shown the behavior of n_{h0} from (31), for an easy understanding of the mobility conditions that correspond to each α value. Figure 6 highlights that both P_{drop} and GOS_2 increase and P_{b1} decreases, if the user mobility increases (i.e., α decreases). The behavior of P_{b1} can be justified by taking into account that the mobility increase reduces the mean channel holding time in a cell with respect to the average unencumbered call duration; hence, the total traffic intensity in a cell decreases. However, if the user mobility increases, a call crosses a greater number of cells during its lifetime and at each cell change it may be dropped with probability P_{b2} due to the handover failure. This fact causes a significant increase in P_{drop}. A similar behavior (except for a scale factor) is obtained for GOS_2. A further validation of these results can be found in [12], where (under different mobility assumptions) the authors prove that user mobility entails a capacity increase in order to guarantee the same blocking requirements of an hypothetical cellular network with fixed users and the same offered traffic.

Under the same assumptions made for the results of figure 6, we have quantified by simulations the impact of the LEO mobility on the FCA-QH performance. We have evaluated the maximum traffic intensity per cell, ρ_{max}, that fulfills the ITU-T requirements shown in section 2 with 10 channels/cell. For instance, we have $\rho_{max} \approx 3$ erl/cell for $\alpha = 0.31$ and $\rho_{max} \approx 2.6$ erl/cell for $\alpha = 0.16$: if the number of handover requests per call doubles, there is about a 13% capacity reduction. A similar trend has been verified for the α values within the LEO range and for different numbers of system channels.

The impact of different mobility assumptions on the performance of a channel allocation technique can be highlighted on the basis of figure 7, which compares the performance of Fixed Channel Allocation (FCA) [10] for the LEO mobility model presented in this section and the Guérin's mobility model[6] that has been shown in [16]. In both cases, we have assumed the same mean mobile sojourn time in a cell and $T_m = 3$ min (i.e., the same n_{h0} value). In the LEO case, we have selected IRIDIUM-like mobility data (i.e., $V_{trk} = 26{,}600$ km/h, $R = 212.5$ km) and we have obtained n_{h0} equal to 3.125 handovers/call. While, in the Guérin's mobility case, we have considered $E[\nu] = 87$ km/h, $R = 1$ km and, according to [16], we have still obtained n_{h0} equal to 3.125 handovers/call. As in the previous graph, we have simulated a parallelogram shaped cellular network with 7 cells per side, 7 cell reuse cluster and 70 system channels. The results in figure 7

[6] In [16] a mobility model suitable for terrestrial cellular systems is presented. The assumptions of this model are: a homogeneous cellular layout; iid and exponentially distributed mobile sojourn times in subsequent cells; uniform traffic. The excess life theorem (8) can be used to relate the distributions of t_{mc1} and t_{mc2}, and we find that now they are equal. The handover generation process is memoryless. Moreover, equations (9)–(18) and (20)–(26) of section 4 can be applied. Finally, in [16] it is shown that $n_{h0} \approx 0.7178/\alpha$ handovers/call, where α is given by $R/\{E[\nu]T_m\}$.

show that P_{b1} values are almost the same in both cases, whereas the Guérin's model entails higher P_{drop} and GOS_2 values than the LEO one. This difference can be justified if we consider that in the LEO mobility model users are more synchronized in their motion[7] and this aspect may favor the management of handovers.

6. Remarks on the handover traffic

A traffic is characterized by both the arrival process and the service time distribution. Under the basic assumptions made in section 3, analytic derivations of the blocking probability usually consider [7,8,17,35,39]: (i) a Poisson arrival process for handovers towards a cell with rate λ_{h} related to λ on the basis of (22); (ii) a handover arrival process cell-to-cell independent; (iii) an exponentially distributed channel holding time in a cell. However, this handover traffic characterization is approximated: generally, channel holding times are not exponentially distributed, as proved by (12); the handover arrival process is not Poisson, as discussed later in this section; handover arrival processes in adjacent cells are correlated, since a user may cross several cells during a call. This section presents some qualitative and quantitative considerations that are useful to characterize the handover arrival process and to evaluate its impact on the performance of channel allocation schemes.

In general, the handover arrival process towards a cell is the aggregation of several contributions coming from adjacent cells. However, in the LEO model of the previous section, the handover arrival process in a cell is derived from the output process of only one adjacent cell.

An interesting parameter to characterize an arrival process is the Index of Dispersion for Counts (IDC) [12]: IDC_t at time t is the variance of the number of arrivals in an interval of length t divided by the mean number of arrivals in t. For Poisson processes, $\mathrm{IDC}_t \equiv 1$, $\forall t$. In general, IDC values greater than 1 highlight a more bursty arrival process than a Poisson one. Whereas, arrival processes with a lower variability than a Poisson one have IDC < 1. The limiting case is a deterministic arrival process, where $\mathrm{IDC}_t \equiv 0$, $\forall t$. For a given distribution of the channel holding time and a given value of the average arrival rate, the blocking probability of a loss queuing system decreases, if we consider arrival processes with lower IDC values.

We use IDC_t to study the handover arrival process offered to a cell. Of course, since the new call arrival process is Poisson, it is characterized by $\mathrm{IDC}_t \equiv 1$, $\forall t$. Whereas, the IDC_t value for the handover arrival process to a cell depends on both the user mobility conditions, the channel allocation technique, the traffic intensity and the number of available channels.

The handover arrival process and the new call arrival process are merged so as to form the input process to the loss queuing system which models the behavior of a cell according to the BCC policy. Since, on the basis of (12), the distributions of the channel holding times for new call attempts and handed-over calls are quite similar[8], IDC differences between the new call arrival process and the handover arrival process will cause different values of the related blocking probabilities. We have evaluated $\mathrm{IDC}_{t=4\ \mathrm{min}}$ for the LEO case (IRIDIUM-like mobility, $\alpha = 0.16$) with FCA by using the same simulation model outlined in section 5. In particular, for a given cell, the number of arrivals have been counted in intervals of 4 minutes for both new call attempts and handover requests. Correspondingly, we have obtained two histograms, as shown in figure 8 in the case of a traffic intensity due to new call attempts ($= \lambda T_{\mathrm{m}}$) equal to 8 erl/cell (we have considered here a heavy traffic case in order to emphasize the impact of the blocking on the arrival process characteristics). These histograms show a higher peak for new calls than for handover requests. This difference is due to the fact that there is a practical limit to the maximum number of handover arrivals in 4 min. In this case, we have obtained $\mathrm{IDC}_{t=4\ \mathrm{min}} \approx 0.98$ for the new call arrival process and $\mathrm{IDC}_{t=4\ \mathrm{min}} \approx 0.56$ for the handover arrival process.

Figure 9 shows $\mathrm{IDC}_{t=4\ \mathrm{min}}$ for the handover arrival process with both Dynamic Channel Allocation (DCA) and FCA for different traffic intensity values due to new call attempts ($= \lambda T_{\mathrm{m}}$). In particular, DCA assigns channels to cells on demand on the basis of a cost-function, as described in [9,10]. We have that $\mathrm{IDC}_{t=4\ \mathrm{min}} < 1$ in all cases for the handover arrival process, so highlighting that the handover traffic has a lower variability than a Poisson one. Moreover, $\mathrm{IDC}_{t=4\ \mathrm{min}}$ decreases as the traffic increases, because we have a higher handover failure probability (i.e., P_{b2}) that produces a smoother handover traffic. Finally, DCA gives greater $\mathrm{IDC}_{t=4\ \mathrm{min}}$ values than FCA for the same traffic intensity values, because DCA allows lower P_{b2} values. We have also verified that IDC_t values slightly reduce as mobility increases (i.e, n_{h0} increases), because a call crosses more cells during its lifetime and at each cell passage the handover traffic is smoothed due to the loss queuing system behavior of a cell. Of course, the IDC values depend on mobility assumptions and channel allocation techniques, but the handover arrival process characteristics that have been outlined above on the basis of the mobility model for LEO-MSSs are generally applicable.

The differences between the handover arrival process and the new call arrival process have an impact on the blocking performance of channel allocation techniques. Since the handover arrival process has a lower variability than the new call arrival process, we expect that P_{b2} is lower than P_{b1} even without any prioritization strategy for handover requests. This interesting consideration has been confirmed by the simulation results shown in fig-

[7] In the LEO mobility model considered in this section, all the users have the same speed, the same motion direction, the same cell sojourn time.

[8] If we look at equation (12), we note that both $f_{\mathrm{tmc1}}(t)$ and $f_{\mathrm{tmc2}}(t)$ are weighted by the same exponential factor $\mathrm{e}^{-t/T_{\mathrm{m}}}$ (which is due to the distribution of t_{d}) and we can consider that they are quite close to each other, in particular if compared on the basis of parameter G introduced in [17].

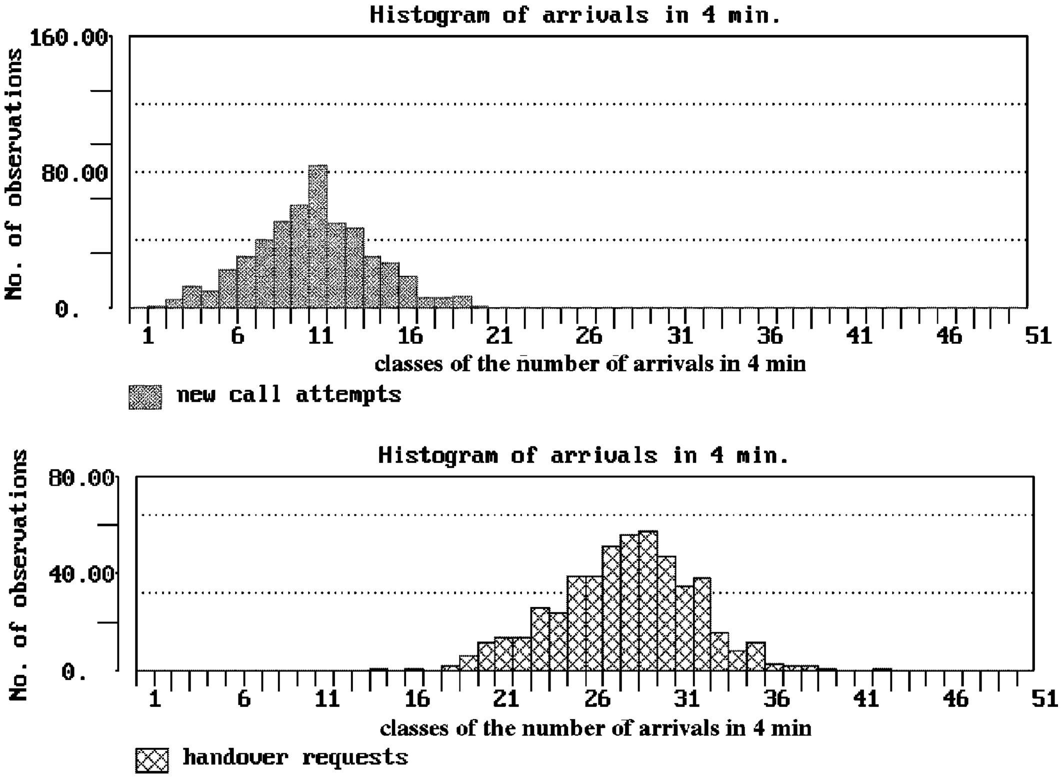

Figure 8. Histograms for the number of both handover arrivals and new call arrivals in 4 min in a cell for a LEO-MSS (IRIDIUM case, $\alpha = 0.16$) with FCA and DCA and a traffic intensity of 8 erl/cell due to new call attempts.

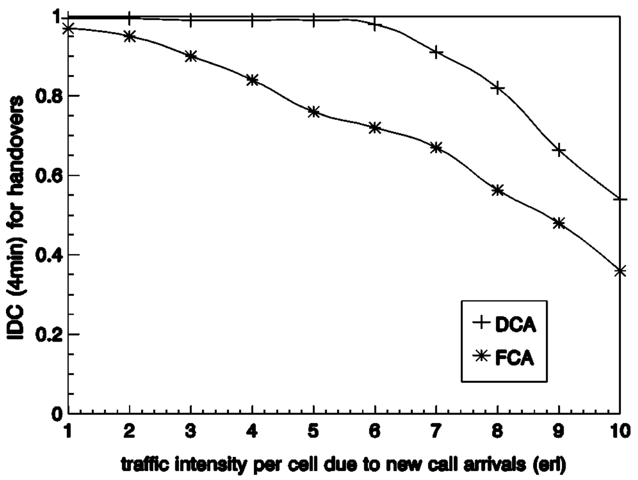

Figure 9. Behaviors of $\mathrm{IDC}_{t=4\ \mathrm{min}}$ for the handover arrival process towards a cell as a function of the traffic intensity due to new call arrivals for a LEO-MSS (IRIDIUM case, $\alpha = 0.16$) with FCA and DCA.

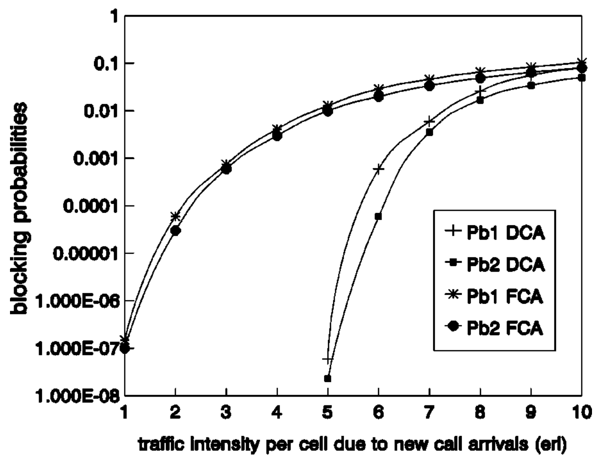

Figure 10. Behaviors of P_{b1} and P_{b2} for a LEO-MSS (IRIDIUM case, $\alpha = 0.16$) with FCA and DCA as a function of the traffic intensity per cell due to new call attempts.

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 $P_{\mathrm{b1}} > P_{\mathrm{b2}}$ (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 blocking 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 $E[t_{\mathrm{H}}]$). Hence, both new calls and handed-over calls have the same handover probability, P_{H}, which is defined as follows:

$$P_{\mathrm{H}} \triangleq \frac{\lambda(1-P_{\mathrm{b1}})}{\lambda(1-P_{\mathrm{b1}})+\lambda_{\mathrm{h}}(1-P_{\mathrm{b2}})} P_{\mathrm{H1}} + \frac{\lambda_{\mathrm{h}}(1-P_{\mathrm{b2}})}{\lambda(1-P_{\mathrm{b1}})+\lambda_{\mathrm{h}}(1-P_{\mathrm{b2}})} P_{\mathrm{H2}}. \quad (32)$$

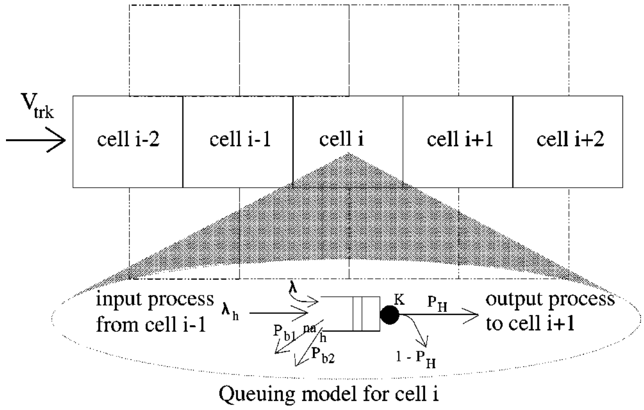

Figure 11. Modeling of a cell with FCA and BCC policy in the LEO mobility case as a loss queuing system and illustration of both input and output processes.

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, $E[t_{\mathrm{H}}]$, that can be deduced from $E[t_{\mathrm{H1}}]$ and $E[t_{\mathrm{H2}}]$ in the same way as P_{H} is obtained from P_{H1} and P_{H2} in (32). Therefore, recalling (15), we have

$$E[t_{\mathrm{H}}] = T_{\mathrm{m}}(1-P_{\mathrm{H}}). \quad (33)$$

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 $\lambda_{\mathrm{h}}/\lambda$ 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 ($z_{\mathrm{na}} = 1$, because it is related to a Poisson process);
- $z_{\text{h-in}}$, handover input process: $z_{\text{h-in}} < 1$;
- $z_{\text{h-out}}$, handover output process (i.e., the handover input process for cell $i+1$);
- $z_{\text{t-in}}$, total input process;
- $z_{\text{t-out}}$, 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: $z_{\text{h-in}} = z_{\text{h-out}} = z_{\mathrm{h}}$. 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]:

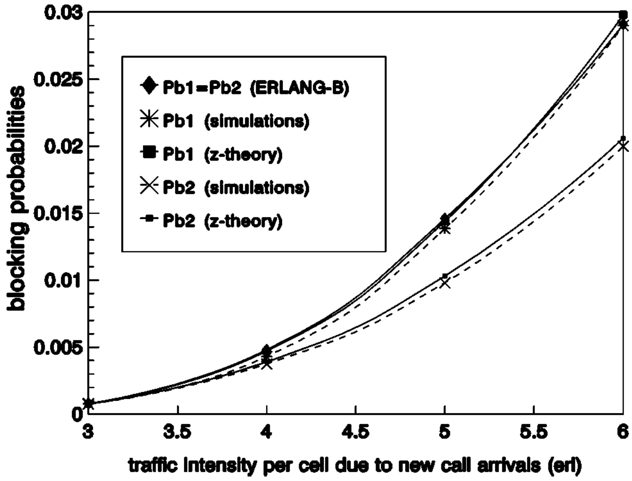

Figure 12. Comparison in the FCA case between simulation results and analytical predictions obtained by means of the new peakedness approach ("z-theory") and the ERLANG-B method.

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

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 obtained from the previous formulas (34)–(39) by assuming $z_\mathrm{h} \equiv 1$ and, hence, $z_\text{t-in} \equiv 1$ (i.e., all input processes are Poisson). Consequently, $P_\mathrm{b1} \equiv P_\mathrm{b2}$ is obtained by the classical ERLANG-B formula. In figure 12 we have denoted as "ERLANG-B" the $P_\mathrm{b1} \equiv P_\mathrm{b2}$ 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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