

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

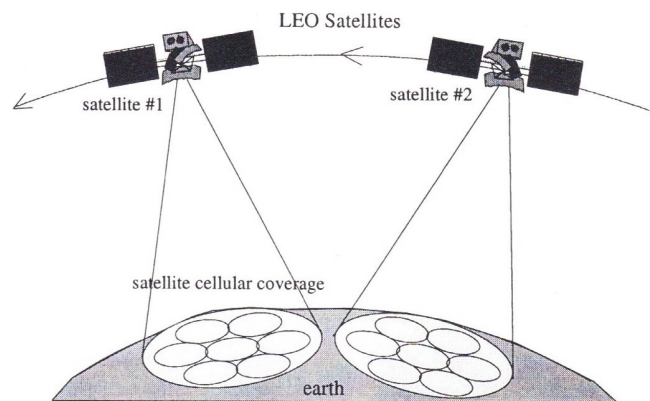


Figure 1. A LEO-MSS with satellite-fixed cells.

motion and to evaluate its impact on the performance of channel allocation techniques.

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

Probabilities P_{drop} and P_{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_{drop} needs a stronger requirement than P_{b1} . The target values for the QoS parameters have been specified by ITU-T [20]: P_{drop} and P_{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_{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_d , is exponentially distributed¹;
- 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_{trk} (e.g., $V_{trk} \approx 26,000$ 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_{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_{drop} , P_{Hi} , n_{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_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 <i>cell radius</i> 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 <i>given cell</i> (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 <i>given cell</i> 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 <i>given cell</i> (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

$$\alpha \triangleq \frac{R}{E[\nu]T_m}, \quad S \triangleq \frac{E[t_{wmax}]}{E[t_{mc2}]}, \quad (1)$$

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 $f_{x_1}(d)$, $f_{x_2}(d)$

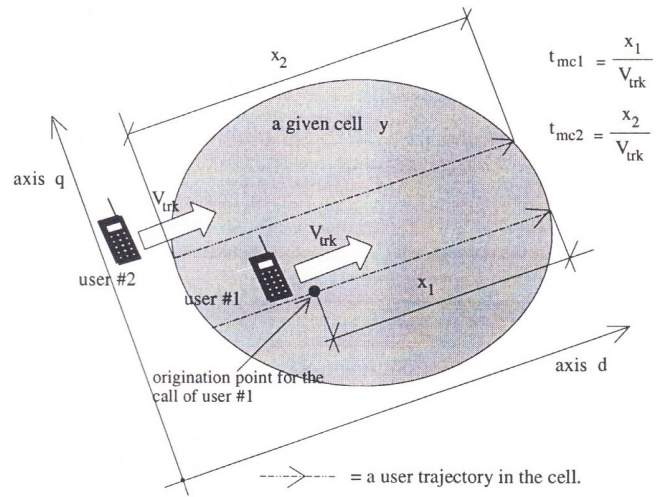


Figure 2. Description of the crossed distance in cell y from the call arrival instant in y for a user that originates a call in this cell (user #1) and for a user with a handed-over call to cell y (user #2).

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 $h(q)dq/A$, where A

is the cell area, while a handed-over call towards cell y crosses this cell with an offset which is uniformly distributed² from q_{\min} to q_{\max} [11]. In conclusion, $f_{x_1}(d)$ and $f_{x_2}(d)$ are

$$\begin{aligned} f_{x_1}(d) &= \int_{q_{\min}}^{q_{\max}} \left[\frac{u(d) - u(d - h(q))}{h(q)} \right] \frac{h(q)}{A} dq, \\ f_{x_2}(d) &= \frac{1}{q_{\max} - q_{\min}} \int_{q_{\min}}^{q_{\max}} \delta(d - h(q)) dq, \end{aligned} \quad (2)$$

where $u(x)$ is the unit step function: $u(x) = 1$ for $x \geq 0$; $u(x) = 0$ 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:

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

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:

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

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

$$t_{mc1} = \frac{x_1}{V_{\text{trk}}}, \quad t_{mc2} = \frac{x_2}{V_{\text{trk}}}. \quad (5)$$

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

$$f_{t_{mc1}}(t) = V_{\text{trk}} f_{x_1}(tV_{\text{trk}}), \quad (6)$$

$$f_{t_{mc2}}(t) = V_{\text{trk}} f_{x_2}(tV_{\text{trk}}). \quad (7)$$

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

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

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,

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

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

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

$$E[t_{mc1}] = \frac{E[x_1]}{V_{\text{trk}}}, \quad E[t_{mc2}] = \frac{E[x_2]}{V_{\text{trk}}}. \quad (9)$$

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, $f_{t_{mci}}(t)$ 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 assumption³ 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 $t_d > t_{mc1}$, whereas a handed-over call served in cell y generates a further handover request if $t_d > t_{mc2}$. 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

$$\begin{aligned} P_{H1} &\triangleq \Pr\{t_d > t_{mc1}\} \\ &= \int_0^{+\infty} \Pr\{t_d > t \mid t_{mci} = t\} f_{t_{mci}}(t) dt \\ &= \int_0^{+\infty} e^{-t/T_m} f_{t_{mci}}(t) dt \end{aligned}$$

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 $f_{t_{mci}}(t)$, 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:

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

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 $t_{mci} = \tau$:

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

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

$$E[t_{Hi}] = \int_0^{+\infty} E[t_{Hi} | t_{mci} = \tau] f_{t_{mci}}(\tau) d\tau \\ = T_m [1 - P_{H1}]. \quad (15)$$

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	$P_{H1}P_{H2}(1 - P_{H2})$
\vdots	\vdots
k	$P_{H1}P_{H2}^{k-1}(1 - P_{H2})$