On the Fixed Channel Reservation Policy in LEO Mobile Satellite Systems

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***Abstract*– We consider a Low Earth Orbit (LEO) Mobile Satellite System (MSS) with "satellite-fixed" cells that accommodates new and handover Poisson arriving calls of different service-classes. By modelling the LEO-MSS as a multirate loss system, we provide an analytical framework for the recursive calculation of call blocking and handover failure probabilities under the Fixed Channel Reservation (FCR) policy. In the FCR policy, an integer number of channels is reserved in order to benefit calls of high channel requirements. The loss model under the FCR policy does not have a Product Form Solution (PFS) for the steady state probabilities. However, we show that the channel occupancy distribution can be calculated via an approximate but recursive formula. Simulation results verify the accuracy of the proposed formulas.**

I. INTRODUCTION

Low Earth Orbit (LEO) Mobile Satellite Systems (MSS) with "satellite-fixed" cells are ideally suited for providing multiservice real time applications to a diverse population in large geographical areas [1]. Compared to geostationary MSS, their requirements in terms of transmit power and transmission delays are lower at the cost of introducing frequent beam handovers to in-service Mobile Users (MUs) during their lifetime in the system. To assure Quality of Service (QoS) in the multirate traffic environment of contemporary LEO-MSS it is essential to develop QoS mechanisms, with efficient and fast QoS assessment, that provide access to the necessary bandwidth needed by the services of the MUs and ensure fairness among different mobile services/applications.

Considering call-level traffic in a LEO-MSS which accommodates different service-classes such a QoS mechanism is a channel sharing policy, since it affects call-level performance measures, like Call Blocking Probabilities (CBP) and handover failure probabilities. The QoS assessment of LEO-MSS under a channel sharing policy can be accomplished through teletraffic loss or queueing models. In the literature, there are various teletraffic loss or queueing models that describe channel sharing policies in single-rate ([2]-[11]) and multirate ([12]-[15]) LEO-MSS.

Herein, we focus on multirate LEO-MSS. To this end, in [12], an analytical framework is proposed for evaluating the performance of the Complete Sharing (CS) and the Fixed Channel Reservation (FCR) policies that are applied in LEO–MSS supporting multirate Poisson traffic. Under the CS policy, all calls have access to the available channels. A call is accepted in a cell whenever the required channels are available. Otherwise the call is blocked and lost. The CS policy is unfair to calls of high channel requirements since it leads to higher CBP. Contrary to the CS policy, the FCR policy can provide QoS guarantee to high speed calls. In the FCR policy, an integer number of channels is reserved to benefit calls of certain service-classes which have higher channel requirements. In [13], apart from the CS and the FCR policies, the Complete Partitioning (CP) and the Threshold Call Admission (TCA) policies are proposed. In the CP policy, the capacity C (in channels) of a cell is partitioned into K subsets, where K is the number of service-classes accommodated in the cell and C_k the capacity of each partition. Each class k (k=1,…,K) is allocated a certain partition. Thus, each cell can be modelled as an $M/M/C_k/C_k$ system. Since the CP policy can lead to poor channel utilization we do not consider it herein. The interested reader may also resort to [14] for an analysis on optimum CP policies. In the TCA policy, new service-class k calls are not allowed to enter a cell if the number of in-service new and handover calls of service-class k plus the new call exceeds a threshold (different for each service-class). In [13], only simulation results are presented for the TCA policy. Later, in [15] an analytical Markovian model is proposed for the TCA policy that allows the determination of the various performance measures (e.g., CBP and handover failure probabilities) by solving the corresponding Global Balance (GB) equations of the K-dimensional Markov chains. This task is computationally extremely complex and time consuming for real systems of large capacity and many service-classes. A similar complex procedure (based on solving a linear system of GB equations) is proposed in the case of the FCR policy in [12], [13].

In this paper we consider a LEO-MSS with "satellite-fixed" cells and focus on the FCR policy. Contrary to the CS, the CP or the TCA policy, the FCR policy destroys reversibility of the K-dimensional Markov chains and therefore no Product Form Solution (PFS) exists for the steady state probabilities. However, we provide efficient formulas for the calculation of the various performance measures under the FCR policy. More precisely, we extend the analysis of [12]-[13] by proposing a recursive formula for the calculation of the channel occupancy distribution. This formula is the springboard for the calculation of CBP and handover failure probabilities. In addition, the proposed formula: a) reduces the computational complexity introduced by the analysis provided in [12]-[13] and b) leads to highly satisfactory results compared to simulation.

The remainder of this paper is as follows: In Section II, we review the LEO MSS model of [13]. In Section III, we prove a recursive formula for the calculation of the channel occupancy distribution in the case of the FCR policy. In Section IV, we present analytical and simulation results for various performance measures, for evaluation. We conclude in Section V.

II. The LEO-MSS Model

A. Description

Following the analysis of [13], we consider a LEO-MSS of N contiguous "satellite-fixed" cells, each modelled as a rectangle of length L (425 km in the case of the Iridium LEO-MSS), that form a strip of contiguous coverage on the region of the Earth. Each cell has a capacity of C channels. The system of these N cells accommodates MUs who generate calls of K different service-classes with different QoS requirements. Each service-class k (k=1,…,K) call requires a fixed number of b_k channels for its whole duration in the system. New and handover calls of service-class k follow a Poisson process with arrival rates λ_k and λ_{hk}, respectively. New calls may arrive in any cell with equal probability. The cell that a new call originates is the source cell. The arrival of handover calls in a cell is as follows: handover calls cross the source cell's boundaries to the adjacent right cell having a constant velocity of $-V_{tr}$, where V_{tr} (approx. 26600 km/h in the Iridium constellation) is the subsatellite point speed. An in-service call that departs from cell N will request a handover in cell 1, thus having a continuous cellular network (Fig. 1).

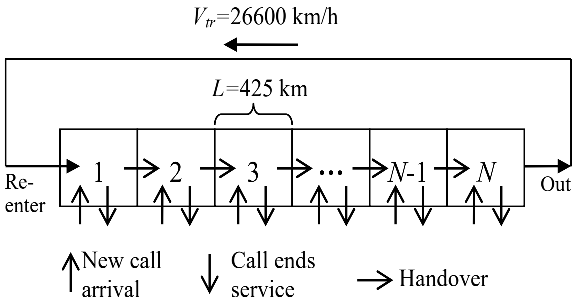

Fig. 1. A rectangular cell model for the LEO-MSS network.

Based on the above, let t_c be the dwell (or sojourn) time of a call in a cell (i.e., the time that a call remains in the cell). Then, t_c is: (i) uniformly distributed between [0, L/V_{tr}] for new calls in their source cell and (ii) deterministically equal to T_c=L/V_{tr} for handover calls that traverse any adjacent cell from border to border. Based on (ii), T_c expresses the interarrival time for all handovers subsequent to the first one. As far as the duration of a service-class k call in the system and the channel holding time in a cell are concerned, they are exponentially distributed with mean T_{dk} and μ_k^{-1}, respectively.

B. Determination of handover arrival rate and channel holding time

To determine formulas for the handover arrival rate λ_{hk} and the channel holding time with mean μ_k^{-1} of service-class k calls, some necessary definitions are required:

1) The (dimensionless) parameter γ_k, is the ratio between the mean duration of a service-class k call in the system and the dwell time of a call in a cell [2]:

$$\gamma_k = T_{dk} / T_c \tag{1}$$

Note that this parameter expresses the average number of handover requests per service-class k call assuming that there is no blocking.

2) The time $T_{h1,k}$, expresses the interval from the arrival of a new service-class k call in the source cell to the instant of the first handover. $T_{h1,k}$ is uniformly distributed between [0, T_c] with probability density function (pdf) [16]:

$$pdf_{T_{h1,k}}(t) = \begin{cases} \dfrac{V_{tr}}{L} & for\ 0 \le t \le \dfrac{1}{\gamma} T_{dk} \\ 0 & \end{cases} \tag{2}$$

3) The probabilities $P_{h1,k}$ and $P_{h2,k}$, express the handover probability for a service-class k call in the source cell and in a transit cell, respectively. Due to the different distances covered by a MU in the source cell and in the transit cells, these probabilities are different. More precisely, $P_{h1,k}$ is defined as [16]:

$$\begin{aligned} P_{h1,k} &= \int_0^{\infty} \Pr\{t_{dk} > t \,|\, T_{h1,k} = t\}\, pdf_{T_{h1,k}}(t)\,dt \\ &= \int_0^{\infty} e^{-t/T_{dk}}\, pdf_{T_{h1,k}}(t)\,dt = \gamma_k (1 - e^{-(1/\gamma_k)}) \end{aligned} \tag{3}$$

where t_{dk} is the service-class k call duration time (exponentially distributed with mean T_{dk}).

The residual service time of a service-class k call after a successful handover request has the same pdf as t_{dk} (due to the memoryless property of the exponential distribution [17]). It follows then that $P_{h2,k}$ can be expressed by:

$$\begin{aligned} P_{h2,k} &= \Pr\left\{ t_{dk} > \frac{L}{V_{tr}} \right\} = 1 - \Pr\left\{ t_{dk} \le \frac{L}{V_{tr}} \right\} \\ &= 1 - \int_0^{T_c} \frac{1}{T_{dk}} e^{-t/T_{dk}}\,dt = e^{-(1/\gamma_k)} \end{aligned} \tag{4}$$

The handover arrival rate λ_{hk} can be related to λ_k by assuming that in each cell there exists a flow equilibrium between MUs entering and MUs leaving the cell. In that case, we may write the following flow equilibrium equation (MUs entering the cell = MUs leaving the cell):

$$\begin{aligned} &\lambda_k (1 - P_{b_k}) + \lambda_{hk} (1 - P_{f_k}) = \\ &\lambda_{hk} + \lambda_k (1 - P_{b_k})(1 - P_{h1,k}) + \lambda_{hk} (1 - P_{f_k})(1 - P_{h2,k}) \end{aligned} \tag{5}$$

where: P_{b_k} is the CBP of new service-class k calls in the source cell and P_{f_k} is the handover failure probability of service-class k calls in transit cells.

The values of P_{b_k} and P_{f_k} will be determined in the next subsection.

The left hand side of (5) refers to new and handover service-class k calls that are accepted in the cell with probability $\lambda_k (1 - P_{b_k})$ and $\lambda_{hk} (1 - P_{f_k})$, respectively. The right hand side of (5) refers to: 1) service-class k calls that are handed over to the transit cell (depicted by λ_{hk}), 2) new calls that complete their service in the source cell without requesting a handover (depicted by $\lambda_k(1-P_{bk})(1-P_{h1,k})$) and 3) handover calls that do not handover to the transit cell (depicted by $\lambda_{hk}(1-P_{fk})(1-P_{h2,k})$).

Equation (5), can be rewritten as:

$$\frac{\lambda_{hk}}{\lambda_k} = \frac{(1-P_{b_k})P_{h1,k}}{1-(1-P_{f_k})P_{h2,k}} \tag{6}$$

To derive a formula for the channel holding time of service-class k calls, we remind that channels are occupied in a cell either by new or handover calls. Furthermore, channels are occupied either until the end of service of a call or until a call is handed over to a transit cell. Since the channel holding time can be expressed as $t_{h1,k} = \min(t_{dk}, t_c)$ in the case of the source cell and $t_{h2,k} = \min(t_{dk}, T_c)$ in the case of a transit cell, then the mean value of $t_{hi,k}$, $E_k(t_{hi,k})$ for i=1,2 is given by [13]:

$$E_k(t_{hi,k}) = T_{dk}(1-P_{hi,k}) \tag{7}$$

We define now by P_k and P_k^h the probabilities that a channel is occupied by a new and a handover service-class k call, respectively. Then:

$$P_k = \frac{\lambda_k(1-P_{b_k})}{\lambda_k(1-P_{b_k})+\lambda_{hk}(1-P_{f_k})} \tag{8}$$

$$P_k^h = \frac{\lambda_{hk}(1-P_{f_k})}{\lambda_k(1-P_{b_k})+\lambda_{hk}(1-P_{f_k})} \tag{9}$$

Based on (7)-(9), the channel holding time of service-class k calls (either new or handover) is approximated by an exponential distribution whose mean μ_k^{-1} is the weighted sum of (7) (for i=1, 2) multiplied by the corresponding probabilities P_k (for i=1) and P_k^h (for i=2):

$$\begin{aligned}\mu_k^{-1} &= P_k E_k(t_{h1,k}) + P_k^h E_k(t_{h2,k}) = \\ &\frac{\lambda_k(1-P_{b_k})E_k(t_{h1,k})}{\lambda_k(1-P_{b_k})+\lambda_{hk}(1-P_{f_k})} + \frac{\lambda_{hk}(1-P_{f_k})E_k(t_{h2,k})}{\lambda_k(1-P_{b_k})+\lambda_{hk}(1-P_{f_k})}\end{aligned} \tag{10}$$

III. A Proposed Recursive Formula for the LEO-MSS Model Based on the FCR Policy

To facilitate the description of the analytical model under the FCR policy, we distinguish new from handover calls and assume that each cell accommodates calls of $2K$ service-classes. A service-class k call is new if $1 \le k \le K$ and handover if $K+1 \le k \le 2K$.

The FCR policy is described as follows: A call of service class k (k =1,…,$2K$) requests b_k channels and has a FCR parameter CR_k that expresses the integer number of channels reserved to benefit calls of all other service-classes except from k. The analysis presented herein is more general compared to [13] since it allows the application of the FCR policy to all calls (new or handover) of a service-class k. In that sense, the FCR policy can be applied to favor handover calls of a service-class against new or handover calls from other service-classes. In [13], the FCR policy can be applied only in order to benefit handover calls of a service-class against new calls from other service-classes.

The GB equation for state $\boldsymbol{n}=(n_1,...,n_k,...,n_{2K})$, expressed as *rate into state* $\boldsymbol{n}$ = *rate out of state* $\boldsymbol{n}$, in the FCR model is given by:

$$\begin{aligned}&\sum_{k=1}^{K}\lambda_k(\boldsymbol{n}_k^-)P(\boldsymbol{n}_k^-) + \sum_{k=K+1}^{2K}\lambda_{kh}(\boldsymbol{n}_k^-)P(\boldsymbol{n}_k^-) + \sum_{k=1}^{2K}(n_k+1)\mu_k P(\boldsymbol{n}_k^+) \\ &= \sum_{k=1}^{K}\lambda_k(\boldsymbol{n})P(\boldsymbol{n}) + \sum_{k=K+1}^{2K}\lambda_{kh}(\boldsymbol{n})P(\boldsymbol{n}) + \sum_{k=1}^{2K} n_k\mu_k P(\boldsymbol{n})\end{aligned} \tag{11}$$

where:

$$\lambda_k(\boldsymbol{n}) = \begin{cases}\lambda_k & for\ C-\boldsymbol{nb} \ge b_k + CR_k \\ 0 & otherwise\end{cases} \tag{12}$$

$$\lambda_{kh}(\boldsymbol{n}) = \begin{cases}\lambda_{kh} & for\ C-\boldsymbol{nb} \ge b_k + CR_k \\ 0 & otherwise\end{cases} \tag{13}$$

$\boldsymbol{n}_k^- = (n_1,...,n_k-1,...,n_{2K})$, $\boldsymbol{n}_k^+ = (n_1,...,n_k+1,...,n_{2K})$ and $P(\boldsymbol{n}), P(\boldsymbol{n}_k^-), P(\boldsymbol{n}_k^+)$ are the probability distributions of states $\boldsymbol{n}, \boldsymbol{n}_k^-, \boldsymbol{n}_k^+$, respectively.

The FCR model does not have a PFS for the determination of the steady state probabilities $P(\boldsymbol{n})$ since LB can be destroyed between adjacent states $\boldsymbol{n}_k^-, \boldsymbol{n}$ or $\boldsymbol{n}, \boldsymbol{n}_k^+$ due to the existence of the FCR parameters. This means that $P(\boldsymbol{n})$'s (and consequently all performance measures) can be determined by solving the set of linear GBs, a realistic task only for cells of very small capacity and two or three service-classes.

Contrary to [13], where it is suggested to apply a linear equation procedure (such as the Gauss-Siedel iteration) for solving the GBs, we prove an approximate but recursive formula for the calculation of the occupancy distribution, $q(j)$, of the FCR model. By definition:

$$q(j) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} P(\boldsymbol{n}) \tag{14}$$

where $\boldsymbol{\Omega}_j$ is the set of states whereby exactly j channels are occupied by all in-service calls, i.e. $\boldsymbol{\Omega}_j = \{\boldsymbol{n}\in\boldsymbol{\Omega} : \boldsymbol{nb} = j\}$.

Since $j=\boldsymbol{nb} = \sum_{k=1}^{2K} n_k b_k$, (14) can be written as follows:

$$jq(j) = \sum_{k=1}^{2K} b_k \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} n_k P(\boldsymbol{n}) \tag{15}$$

To determine the $\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} n_k P(\boldsymbol{n})$ in (15), we assume that Local Balance (LB) exists between states $\boldsymbol{n}_k^-, \boldsymbol{n}$ and has the following form:

$$a_k(\boldsymbol{n}_k^-)P(\boldsymbol{n}_k^-) = n_k P(\boldsymbol{n}) \tag{16}$$

where: $a_k(\boldsymbol{n}_k^-) = \begin{cases}\lambda_k(\boldsymbol{n}_k^-)/\mu_k, & k=1,...,K \\ \lambda_{kh}(\boldsymbol{n}_k^-)/\mu_k, & k=K+1,...,2K\end{cases}$.

Summing both sides of (16) over $\boldsymbol{\Omega}_j$ we have:

$$\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} a_k(\boldsymbol{n}_k^-)P(\boldsymbol{n}_k^-) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} n_k P(\boldsymbol{n}) \quad (17)$$

The left hand side of (17) can be written as:

$$\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} a_k(\boldsymbol{n}_k^-)P(\boldsymbol{n}_k^-) = a_k(j-b_k)q(j-b_k) \quad (18)$$

where:

$$a_k(j\text{-}b_k) = \begin{cases} a_k & for\ \ j \le C - CR_k \\ 0 & otherwise \end{cases} \quad (19)$$

Based on (17)-(19), we write (15) as follows:

$$q(j) = \begin{cases} 1 & for\ j=0 \\ \frac{1}{j}\sum_{k=1}^{2K} a_k(j-b_k)b_k q(j-b_k) & for\ j=1,...,C \\ 0 & otherwise \end{cases} \quad (20)$$

Based on (20), the values of P_{b_k} (k=1,…,K) can be determined via the formula:

$$P_{b_k} = \sum_{j=C-b_k-CR_k+1}^{C} G^{-1}q(j) \quad (21)$$

where $G = \sum_{j=0}^{C} q(j)$ is the normalization constant.

Similarly, the values of P_{f_k} (k=K+1,…,2K) can be determined via the formula:

$$P_{f_k} = \delta_k \sum_{j=C-b_k-CR_k+1}^{C} G^{-1}q(j) \quad (22)$$

where δ_k is a correction factor introduced in order to model the dependency between successful handovers of a service-class k call prior to a handover failure. More precisely, a handover failure may occur during the $E_k(n_{hk})$ th handover if an accepted call has already performed $E_k(n_{hk})$ -1 successful handovers, i.e.:

$$\delta_k = (1-P_{b_k})P_{h1,k}(1-P_{f_k})^{E_k(n_{hk})-2}P_{h2,k}^{E_k(n_{hk})-2} \quad (23)$$

where $E_k(n_{hk})$ is given by:

$$E_k(n_{hk}) = \frac{(1-P_{b_k})P_{h1,k}}{1-(1-P_{f_k})P_{h2,k}} \quad (24)$$

Having calculated $q(j)$'s, P_{b_k} and P_{f_k} the following performance measures can be determined:

a) The call dropping probability of service-class k calls, P_{d_k}, which refers to new calls that are not blocked but they are forced to terminate due to handover failure [13]:

$$P_{d_k} = \frac{P_{fk}P_{h1,k}}{1-P_{h2,k}(1-P_{fk})} \quad (25)$$

b) The unsuccessful call probability of service-class k calls, P_{us_k}, which refers to calls that they are either blocked in the source cell or dropped due to a handover failure [13]:

$$P_{us_k} = P_{b_k} + P_{d_k}(1-P_{b_k}) \quad (26)$$

IV. Evaluation

In this section, we present an application example and provide analytical results of the CBP, the handover failure probability, the call dropping probability and the unsuccessful call probability for the proposed formulas. Analytical results are compared to simulation results. The latter are derived via the Simscript III simulation language [18] and are mean values of 7 runs. In each run, twenty million calls are generated. Due to stabilization time, we exclude the blocking events of the first 3% of the generated calls. Confidence intervals of the results are found to be very small and are not presented in Fig. 2 below. For the simulation of the LEO-MSS we adopt the Iridium parameters. The simulated network consists of N = 7 contiguous cells. The subsatellite point speed is V_{tr} = 26600 km/h and the length of each cell is L = 425 km resulting in a maximum dwell time of a call in a cell equal to 57.5 s. MUs are uniformly distributed in the network of cells and new calls may arrive anywhere within the network. In addition, no distortion in the propagation links is considered.

In the application example, each cell has a capacity of C = 40 channels and accommodates Poisson arriving calls of two service-classes which require $b_1 = 1$ and $b_2 = 5$ channels, respectively. We further assume that T_{d1} = 180 s, T_{d2} = 540 s, while the offered traffic per cell is α_1 = 16 erl and α_2 = 0.4 erl. In the case of the FCR policy, the FCR parameters for the new calls of each service-class are: CR_1 = 4 and CR_2 = 0 channels, respectively. This selection achieves CBP equalization among new calls of both service-classes, since $b_1 + CR_1 = b_2$.

In the x-axis of Fig. 2, the traffic loads α_1 and α_2 increase in steps of 1 and 0.1 erl, respectively. So, point 1 represents the offered traffic-load vector (α_1, α_2) = (16.0, 0.4), while point 7 refers to the vector (α_1, α_2) = (22.0, 1.0). The term $P_{\mathrm{b,eq}}$ in Fig. 2 refers to the equalized CBP of both service-classes (achieved due to the selected FCR parameters). According to Fig. 2, we deduce that: i) the accuracy obtained by the proposed formulas compared to simulation is highly satisfactory and ii) increasing the offered traffic-load results in the increase of all performance measures.

V. Conclusion

In this paper, we consider the fixed channel reservation policy and provide an analytical framework for the efficient calculation of various performance measures in a LEO mobile satellite system with "satellite-fixed" cells. The proposed analytical formula for the channel occupancy distribution is recursive and has low computational complexity compared to the methodologies already proposed in the literature which are based on solving extremely large systems of linear global balance equations.

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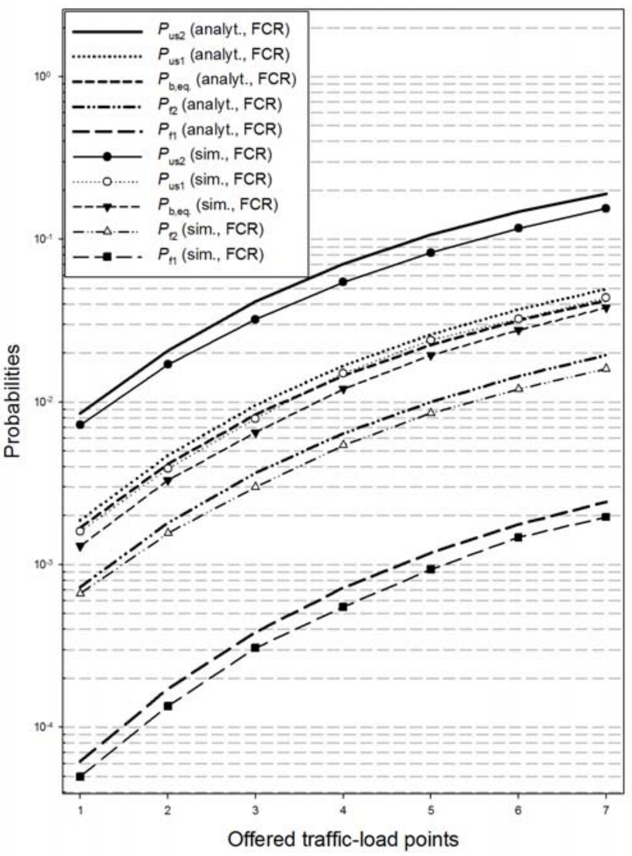

Fig. 2. FCR policy – Both service-classes.