Multilayer hierarchical integration of terrestrial/aeronautical platform segments

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A hierarchical terrestrial/stratospheric cellular network with subscribers of varying mobility characteristics is considered. The stratospheric aeronautical platform adopts an antenna array in order to form beams that overlay clusters of terrestrial cells and provide primary access for platform-only subscribers. The platform also provides hotspot relief for call attempts from terrestrial/platform dual subscribers. An analytical model for the multilayer hierarchical network is developed in order to evaluate its teletraffic performance in terms of call blocking and handover failure probabilities as well as the traffic carrying capacity and channel utilization. Various procedures are adopted in order to minimize the premature termination of calls in progress and satisfy fairness between different categories of users. Numerical results are presented and discussed.

هذا البحث يهدف الى عرض تصور لعملية التكامل الهرمى فى الخدمات بين طبقة الشبكة الأرضية الخليوية وبين منصة الاتصال الجوية لتقديم خدمة الاتصالات اللاسلكية للمشتركين الذين تتعدد خصائص حركتهم فى نطاق الشبكة. تعمل منصة الاتصال الجوية كطبقة عليا تستخدم هوائيات مصفوفية لتغطية مناطق خدمة الشبكة الأرضية اللاسلكية. تقدم طبقة المنصات الجوية الخدمة الأساسية للمشتركين الذين ليس لديهم خدمة اتصال أرضية. وتعمل كذلك على دعم خدمة الاتصال للمشتركين الذين حاولوا الاتصال عن طريق الشبكة الأرضية ولم يتمكنوا من الحصول على الخدمة. ولقد تم فى هذا البحث بناء نموذج رياضى لشبكة متعددة الطبقات لتقييم أدائها من حيث معدل فقد المكالمات. وسعة الشبكة. ومعدل استغلال القنوات. ولقد تم اقتراح مجموعة من الإجراءات لتقليل معدل انقطاع المكالمة أثناء الحديث فى خلال عملية العبور من خلية إلى أخرى. وكذلك تحقيق التوازن فى الخدمة بين مجموعات المشتركين المختلفة.

Key words: Multilayer, Cellular systems, Resource management, High-altitude platform

1. Introduction

The demand for wireless communication services increases exponentially [1]. This demand has a random nature, i.e., random space-time variation of traffic load during the day. To solve this problem using terrestrial cellular systems alone, a large infrastructure is needed; a process that definitely contributes to extremely high cost and long delay. On the other hand, the next-generation mobile communication system should provide a wide range of services universally. This worldwide coverage could be achieved by means of a space segment integrated with a terrestrial segment. The space segment may be based on non-geostationary low earth orbit satellites [2] or High Altitude Platforms (HAPs) [3. Flying in lower stratosphere (17-24 km), the HAPs are combining some of the best characteristics of terrestrial and satellite communication systems while avoiding many of their drawbacks [4]. They are promising large but stationary coverage area, simplified cell planning, low propagation delays, broadband capability, small size of antenna and terrestrial terminal equipment, easy maintenance and upgrading of the payload during the lifetime of the platform, less ground-based communications structure, etc. Although stationary when in operation they can easily be moved in compliance with changing communication demands, thus providing network flexibility [5] and re-configurability [6]. The HAP at a height of 21 km covers an area of radius of 510 km [1]. The HAP employs multi-beam antenna arrays to create contiguous cells on the earth's surface. The sizes and locations of cells can be varied by controlling the array elements and phases. The communication within the area covered by the HAP, with other HAPs, and to a fixed PSTN is controlled by a Ground Control and Switching Centre (GCSC).

Employing a hierarchical multilayer cellular structure can provide high system capacity [7], efficient channel utilization [8], and an inherent load-balancing capability [9]. The advent of a HAP-based network introduces a new dimension to terrestrial cellular communications [10]. Although the degree of integration between terrestrial and stratospheric-based segments remains to be agreed, some points are becoming clear: the platform segment will extend the radio coverage to regions where terrestrial coverage is deemed uneconomical, e.g. sparsely populated rural areas, or impractical, e.g. maritime and aeronautical communities. In this type of system, calls that are denied access in the terrestrial network flow over to the aeronautical platform segment which is superimposed on a number of terrestrial cells. Another relevant feature of the next generation systems is that mobile stations will be tailored to users 'necessities which could indicate that a situation where platform-only, terrestrial-only and dual mode terminals coexist can be envisaged.

In this paper, a stratospheric/terrestrial wireless communication system with multiple hierarchical cellular overlays is considered. For dual mode subscribers, call attempts are first directed to a terrestrial cellular network, with platforms providing necessary overlay. The teletraffic analysis of such network is generally a complex problem. When interaction between the different segments of an integrated system is considered, complexity increases. The present paper introduces an analytical model for teletraffic performance evaluation of a multilayer hierarchical overflow network that gives the handover requests a priority access to channels. Throughout the analysis, the model remains within the framework of a birth-death process. Theoretical performance characteristics for users having different motilities are calculated and presented.

2. Mobility model

The HAP covers a large geographical area tessellated by contiguous cells formed by its beams as shown in fig. 1. The coverage area may be traversed by a large number of mobile users belonging to different environments. These may include office users requests for wireless service in a way similar to that provided by the fixed network. Consequently, no handover is experienced for this traffic stream and users only benefit from the wireless access. Outdoor environment is another source of traffic stream. This stream can be further classified into vehicular users and pedestrian users. The HAP, due to its soft infrastructure and ease of installation, can assist as a teletraffic hot-spot relief to the terrestrial mobile radio network. It is envisaged that Mobile Stations (MSs) on the terrestrial mobile radio network with a dual (terrestrial/HAP) connection mode capability, when finding no free channels in the terrestrial network, can access the HAP network and be assigned a channel if there is any. This access to the HAP network for the dual mode users may be restricted to the handover requests or may be allowed for both handover as well as originated calls.

The moving behaviour of MSs in the covered region is important as it determines the interesting issues involved in the network such as the offered traffic, the handover rate, the radio resource management, and the guaranteed quality of service. Consequently, different mobility-related parameters should be carefully investigated. As a consequence of the user's mobility, handovers of calls in progress may occur; a process which results in an occupation time of a call within the cell being smaller than the call duration. This channel occupation time within a cell is dependent on the network parameters such as the cell size, mobile user location, user speed and call duration. Therefore, the mobile sojourn time in a cell (sometimes called the cell residence time) is important to be determined as it reflects the user mobility. The mobility model should consider the size and shape of the cells and the speed and direction of mobile users. Consider the coverage area of the k^{th} cell formed by the HAP, it has an elliptical shape [1]. We assume that the spatial distribution of users is uniform over the area of the cell such that calls may be originated at any point within it.

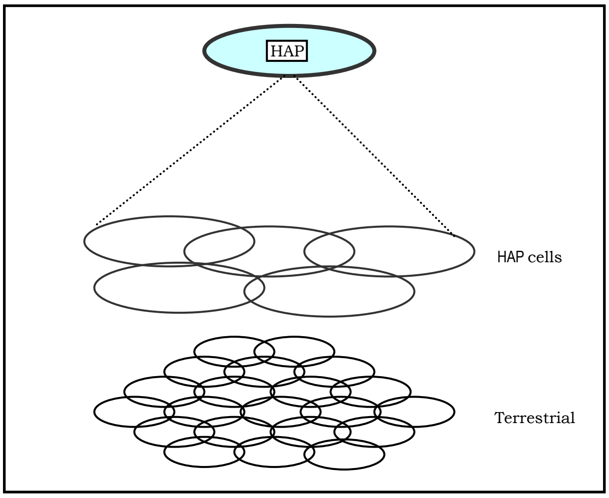

Fig. 1. The hierarchical multiayer cellular structure.

3. Analytical teletraffic model

3.1. Traffic streams

The arrival rate for channel request to the HAP cell is composed of a set of traffic streams as follows (fig. 2):

i) Call rate λ_i generated by office users with hand-held portables. As those users are stationary or nearly stationary, cell boundary crossing while having calls in progress is less probable. Consequently, handover of this sort of traffic is not needed and the period of time during which the channel is occupied by a call is the same as the call duration, T_c.

ii) New call rate λ_{nv} initiated by vehicular users in the cell. Those users will experience many cell boundary crossings during the lifetime of the call and hence require handovers. The holding time of a channel in the cell by this type of calls depends on the total call duration and the sojourn time of the mobile in the serving cell which in turn depends on the cell size and the mobile speed of the vehicular user.

iii) Handover call rate λ_{hv} generated when vehicular users involved in calls experience cell boundary crossings. This rate depends on the new call rate of high mobility users that is accepted by the network, the grade of service of the network and the mobility behaviour of the users.

iv) New call rate λ_{np} initiated by pedestrians on streets of the cell. The call of this sort of traffic will experience less handovers than the last (vehicular) category during the call duration.

v) Handover call rate λ_{hp} generated when pedestrians involved in calls experience cell boundary crossings.

vi) New call rate overflowed from the terrestrial network generated by those mobile users having dual mode terminals. Those calls will only be directed to the HAP network when their access is denied to the terrestrial cellular network. Let P_{BT} denote the probability of access denying of new calls at the terrestrial network and λ_{niT} denote the new call rate initiated at the terrestrial network. If β represents the fraction of the terrestrial users that has dual mode terminals, the new call rate placed by terrestrial users on the HAP cell is $\lambda_{nT} = \beta\lambda_{nT}P_{BT}$. Depending on the user's speed category, the channel occupancy time of this type of overflow calls -if accepted by the HAP network- is the same as those calls belonging to the HAP network, i.e., vehicular and pedestrian users. Once the call is accepted by the HAP network, it is assumed that it is retained by the HAP network until completion.

vii) Handover call rate overflowed from the terrestrial network generated by dual mode mobile users involving in calls when finding no available channels in their terrestrial networks. Let P_{fhT} denote the probability of handover failure at the terrestrial network and λ_{hiT} represent the handover call rate requested at the cell boundary of the terrestrial network. The handover call rate placed by terrestrial users on the HAP network is $\lambda_{hT} = \beta\lambda_{hT}P_{fhT}$. The cell boundaries in the terrestrial and HAP structure may not coincide and the handover calls overflowed from the terrestrial network my enter the HAP network at any point in the cell. The channel occupancy time of this type of overflow handover calls, if accepted by the HAP network, is also the same as those calls of the HAP network due to the memoryless property of the negative exponentially distributed call duration.

Consequently, the mean total call arrival rate, λ_t, offered to a cell of the HAP network is the aggregate traffic of different types, i.e.,

$$\lambda_t = \lambda_{nA} + \lambda_{hA} + \lambda_{TCS}, \tag{1}$$

where,

$\lambda_{nA} = \lambda_i + \lambda_{nv} + \lambda_{np}$, $\lambda_{hA} = \lambda_{hv} + \lambda_{hp}$ and $\lambda_{TCS} = \lambda_{nT} + \lambda_{hT}$

3.2. Resource sharing protocol

We consider a cellular structure formed by the beams of the antenna of the HAP as shown in fig. 1. The interaction between cells is through handovers. Assuming that the rate of incoming handovers is equal to the rate of outgoing handovers, the behaviour of the cells is statistically independent. Each cell is assigned N channels. Out of the N channels, we let N_h channels to be exclusively reserved for handover calls. Further, we keep N_A channels away from the access of the overflowed new calls from the terrestrial network. Consequently, the arriving calls of different categories are served based on the following protocol (c.f. fig. 2):

i) For those new calls overflowed from the terrestrial network, their access is accepted by the HAP network only if there are less than (N-N_h -N_A) calls in the cell. Otherwise, the call is blocked and cleared from the network. We denote this blocking probability as P_B .

ii) A new call initiated by an HAP user (whether it is an office, vehicular or pedestrian user) will be accommodated by an HAP cell if the number of available channels in the cell is (N-N_h). We denote the access denying of these calls as P_{BA}.

iii) A handover call belonging to the HAP network or overflowed from the terrestrial network is served as long as there is at least one of the N channels being free. If all channels are being busy on the arrival of an overflowed terrestrial handover request, the overflow terrestrial handover is failed with probability P_{fh} whence the call is dropped and prematurely terminated.

vi) For those handover requests belonging to the HAP network, when finding all the N channels of the cell being busy on their arrival, we allow the handover request to join a finite queue of length L, waiting for a free channel and retaining connection on the old channel as long as the received signal strength is adequate. The overlap area between cell coverage can be utilised to assist implementing this scenario. We consider that the time during which a MS resides in this overlap area is a random variable T_q that is exponentially distributed with a mean value of $\overline{T}_q = \mu_q^{-1}$. Presuming that there is a free position in the queue; should a channel become available, the old channel is released and the call is handed over to the current cell on the new channel. If the signal level of the call deteriorates relative to the receiver threshold before a channel become available, the handover fails and the call is dropped. We denote this probability of handover failure of HAP requests as P_{fhA}. If the handover request arrives while there is no free positions in the queue, the call is lost. The probability of this occurrence is denoted as P_{loss} . Therefore, the probability that an HAP handover request being failed is given by $P_{drop} = P_{loss} + (1 - P_{loss})P_{fhA}$.

3.3. Channel occupancy time

The channel occupancy time in a cell by a call is a random variable defined as the period of time during which the channel is occupied by a call until the channel is released either by handing over the call to an adjacent cell or the call is completed in the cell. Consequently, there are two processes incorporating to the release of an occupied channel; namely, the completion rate per call and the handover departure rate per call. The call duration of a user is defined as the period of time during which the user is involved in a call irrespective of handovers. It is well known [11] that the call duration follows a negative exponential distribution. Consequently, the probability that a random call will end in a time duration t is,

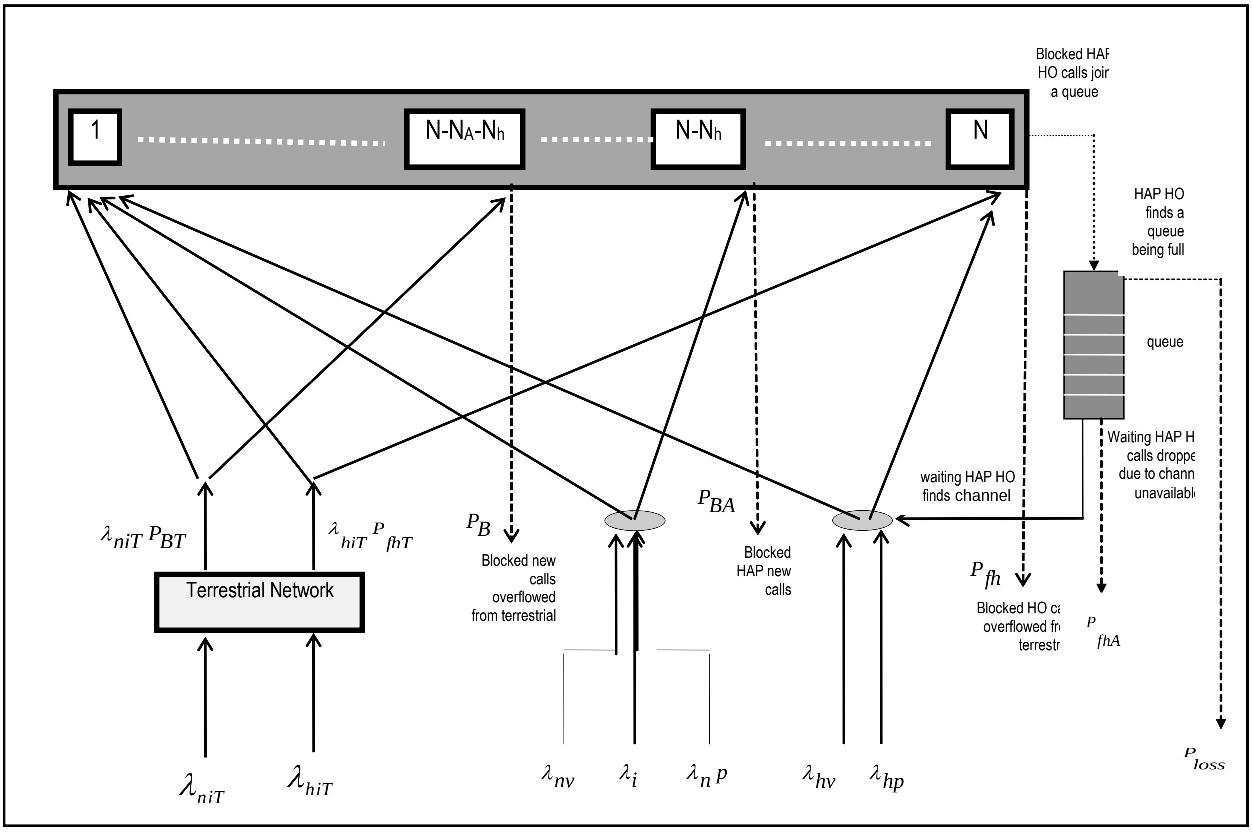

Fig. 2. Channel management at the HAP cell.

$$F_{T_c}(t) = 1 - e^{-\mu_c t}, \tag{2}$$

where $\overline{T_c} = \mu_c^{-1}$ is the average call duration. Therefore, μ_c is the call completion rate (sometimes called service rate) per call.

The time duration during which an MS resides in a serving cell is called the residing time, the dwell time or the sojourn time. The mean sojourn time is influenced by the moving speed of the MS and the coverage area of the cell. Thus, it is different for each mobility category. Consider a vehicular user with a sojourn time in a cell denoted by T_v. We assume, for mathematical tractability, that T_v is a random variable that has a negative exponential distribution of mean $\overline{T}_v = \mu_v^{-1}$, i.e.,

$$f_{T_v}(t) = \mu_v \, e^{-\mu_v t} \; . \tag{3}$$

Therefore, μ_v is the handover departure rate per vehicular call. Based on the fluid flow model, the parameter μ_v can be approximated by [11]:

$$\mu_v = \frac{L \, V_v}{\pi \, S}, \tag{4}$$

where V_v is the speed of the vehicular mobile, L is the length of the perimeter of the cell and S is the cell area. Substituting for the corresponding parameters of the elliptically shaped cell we get:

$$\mu_v = \frac{V_v}{\pi \, (a_k b_k)} \left\{ 1.5 \, (a_k + b_k) - \sqrt{a_k b_k} \; \right\}. \tag{5}$$

Accordingly, the rate of channel release in a cell due to vehicular calls is $\mu_{Hv} = (\mu_v + \mu_c)$. Consequently, the *pdf* of the channel occupancy time of a call due to vehicular user is given by:

$$f_{T_{Hv}}(t) = (\mu_v + \mu_c)\ e^{-(\mu_v+\mu_c)t}\ , \tag{6}$$

with a mean value of :

$$\overline{T}_{Hv} = 1/\mu_{Hv} = (\mu_v + \mu_c)^{-1}\,. \tag{7}$$

With a Similar approach, we get an average channel occupancy time for a call due to pedestrian users as:

$$\overline{T}_{Hp} = 1/\mu_{Hp} = (\mu_p + \mu_c)^{-1}\,. \tag{8}$$

The mean channel holding time of the merged traffic carried by a cell is equal to the composite holding time of all traffic types when weighted with their occurrence probabilities. The mean total call arrival rate offered to a cell of the HAP network is λ_t . The carried rate, λ_c , is given by:

$$\begin{aligned}\lambda_c &= \lambda_{nT}[1-P_B] + \lambda_{nA}[1-P_{BA}] + \lambda_{hT}[1-P_{fh}] \\ &+ \lambda_{hA}[1-P_{drop}].\end{aligned} \tag{9}$$

Let γ_i denote the probability that the served call is being due to the i^th^ traffic stream, we have:

$$\begin{aligned}&\gamma_1 = \lambda_i(1-P_{BA})/\lambda_c\,,\\ &\gamma_2 = \left[\lambda_{nv}(1-P_{BA})+\lambda_{hv}(1-P_{drop})\right]/\lambda_c\,,\\ &\gamma_3 = \left[\lambda_{np}(1-P_{BA})+\lambda_{hp}(1-P_{drop})\right]/\lambda_c \text{ and}\\ &\gamma_4 = \left[\lambda_{nT}(1-P_B)+\lambda_{hT}(1-P_{fh})\right]/\lambda_c\,.\end{aligned} \tag{10}$$

Note that $\sum_{i=1}^{4}\gamma_i = 1$. Consequently, the average composite channel holding time, $\overline{T}_H$, of a randomly chosen call served by the BS is given by:

$$\begin{aligned}\overline{T}_H &= \mu_H{}^{-1}\\ &= \frac{\gamma_1}{\mu_c} + \frac{\gamma_2}{\mu_c+\mu_v} + \frac{\gamma_3}{\mu_c+\mu_p}\\ &+ \gamma_4\left[\frac{\alpha}{\mu_c+\mu_v} + \frac{1-\alpha}{\mu_c+\mu_p}\right],\end{aligned} \tag{11}$$

where, α refers to the fraction of that overflowed traffic from terrestrial network that belongs to vehicular users.

3.4. Handover requirements probabilities

The probability, P_{hv}, that a call in progress due to a vehicular user will require a handover before completion is equal to the probability that the call duration (or the residual call duration) is greater than the mobile sojourn time in the serving cell, i.e.,

$$P_{hv} = \int_0^\infty e^{-\mu_c t}.f_{T_v}(t)dt = \mu_v(\mu_c + \mu_v)^{-1}\,. \tag{12}$$

The probability that a vehicular user's call will terminate before leaving the cell, and therefore will not request handover is given by:

$$P_{tv} = 1 - P_{hv} = \mu_c(\mu_c + \mu_v)^{-1}\,. \tag{13}$$

Let P_{hp} denote the probability that an ongoing call of a pedestrian user will request handover before completion. In a similar approach, P_{hp} is given by:

$$P_{hp} = \mu_p(\mu_c + \mu_p)^{-1}\,. \tag{14}$$

3.5. Handover arrival rates and average handover frequency per call

The handover request rate arrived at the cell is a function of the blocking probability of new calls, the new call rate, the handover requirements probabilities, etc. Based on the assumption that the sojourn time in the cell is exponentially distributed, we consider that the emerged handover rate is Poissonian distributed as well as the merged traffic. To drive an expression for the handover request arrival rate, we consider that there is an equilibrium flow between the incoming and outgoing handover traffic in a cell. As the arrival or departure of a MS to or from a cell is dependent on its speed, we consider the handover rate for each category separately. Therefore, for vehicular users, we have the following equilibrium condition for the handover requests:

$$\lambda_{hv} = \lambda_{nv}[1-P_{BA}]P_{hv} + \lambda_{hv}[1-P_{drop}]P_{hv}, \tag{15}$$

which gives a handover request arrival rate for vehicular users as

$$\lambda_{hv} = \lambda_{nv}\left(\frac{[1-P_{BA}]\ P_{hv}}{1-[1-P_{drop}]\ P_{hv}}\right). \tag{16}$$

The average handover frequency for a call placed by a vehicular user during its lifetime is given by:

$$H_v = \frac{\lambda_{hv}}{\lambda_{nv}} = \frac{[1-P_{BA}]\ P_{hv}}{1-[1-P_{drop}]\ P_{hv}} \ . \tag{17}$$

Similarly, the handover request arrival rate for pedestrian users is given by:

$$\lambda_{hp} = \lambda_{np}\left(\frac{[1-P_{BA}]\ P_{hp}}{1-[1-P_{drop}]\ P_{hp}}\right) , \tag{18}$$

and the average handover frequency for a call placed by a pedestrian user during its lifetime is given by:

$$H_p = \frac{\lambda_{hp}}{\lambda_{np}} = \frac{[1-P_{BA}]\ P_{hp}}{1-[1-P_{drop}]\ P_{hp}} \ . \tag{19}$$

Consequently, the handover rate due to AP users is given by:

$$\Lambda_{hA} = \lambda_{hv} + \lambda_{hp} \ . \tag{20}$$

4. Performance evaluation parameters

The analytical model can provide a means to estimate the important network parameters that can be used to gauge the network performance under different teletraffic scenarios. These include the access denying probability of newly originated calls, the handover failure probability, the forced termination (or call dropping) probability, the handover rate in the cell when a specific new call rate is generated, the average number of handovers a call will experience in its lifetime, the carried traffic by the network under a specific load and certain blocking probability, the channel utilisation or throughput, the average idle time of a channel in the network, etc. The state of the cell in the queuing theory terminology refers to the sum of the number of channels being busy in the cell and the number of handover requests being waiting in the queue. The probability that there are j users (in service and waiting) in the cell is denoted by P_j. Based on the birth-death process at the cell under the channel sharing policy adopted, the state transition diagram of the cell is shown in fig. 3. With the aid of the state transition diagram, we get the state probability of the HAP cell, P_j , as:

$$P_j = \begin{cases} \dfrac{{\lambda_t}^{j}}{j!\ {\mu_H}^{j}} P_0 & \ldots\ldots\ldots\ldots 1 \le j \le (N-N_A-N_h) \\[2ex] \dfrac{{\lambda_t}^{(N-N_A-N_h)}(\lambda_{nA}+\lambda_{hA}+\lambda_{hT})^{j-(N-N_A-N_h)}}{j!\ {\mu_H}^{j}} P_0 & \ldots\ldots (N-N_A-N_h+1) \le j \le (N-N_h) \\[2ex] \dfrac{{\lambda_t}^{(N-N_A-N_h)}(\lambda_{nA}+\lambda_{hA}+\lambda_{hT})^{N_A}(\lambda_{hA}+\lambda_{hT})^{j-(N-N_h)}}{j!\ {\mu_H}^{j}} P_0 & \ldots (N-N_h+1) \le j \le N \\[2ex] \dfrac{{\lambda_t}^{(N-N_A-N_h)}(\lambda_{nA}+\lambda_{hA}+\lambda_{hT})^{N_A}(\lambda_{hA}+\lambda_{hT})^{N_h}(\lambda_{hA})^{j-N}}{N!\ {\mu_H}^{N}\ \prod_{k=1}^{j-N}(N\mu_H+k\mu_q)} P_0 & \ldots N+1 \le j \le N+L , \end{cases} \tag{21}$$

and the idle cell state probability, p_0, is obtained from setting the summation of all probabilities to 1.

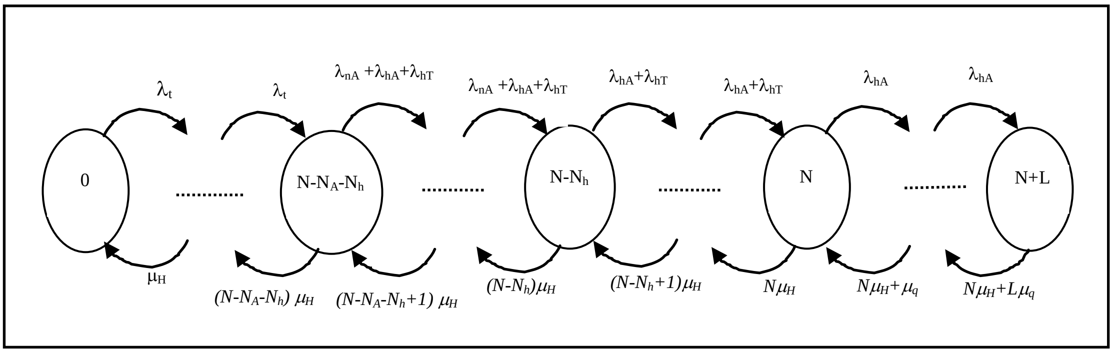

Fig. 3. State transition diagram of the HAP cell.

4.1. Blocking probabilities

The probability P_B that a new call overflowed from the terrestrial network will be denied access to the HAP network is:

$$P_B = \sum_{j=N-N_A-N_h}^{N+L} P_j \quad , \tag{22}$$

and consequently, the overall blocking probability of a dual mode newly initiated call on the terrestrial and HAP network is given by:

$$P_{BB} = P_{BT} \ P_B \quad . \tag{23}$$

The blocking probability of HAP new calls either by an office, vehicular or pedestrian users is given by

$$P_{BA} = \sum_{j=N-N_h}^{N+L} P_j \quad . \tag{24}$$

4.2. Handover failure probabilities

The probability that a handover request overflowed from the terrestrial network will fail at the HAP network, P_{fh}, is:

$$P_{fh} = \sum_{j=N}^{N+L} P_j \ . \tag{25}$$

A handover request of the HAP network when finding all channels being busy on its arrival will join a queue. However, due to the limited number of waiting positions in the queue, the handover request may arrive while there is no free space in the queue, whence the calls is lost. The probability of this occurrence, P_{loss} , is given by:

$$P_{loss} = P_{j=N+L} \ . \tag{26}$$

For those handover requests succeeded to join the queue, it should proceed to the top of the queue and get channel before leaving the overlap area. Given that a handover attempt find a position on the queue, the probability that a handover request fails is:

$$P_{fhA} = \sum_{k=0}^{L} P_{j+k}$$

$$\left[1 - \left\{ \frac{N\mu_H}{N\mu_H + \mu_q} \prod_{i=1}^{k} \ 1 - \left(\tfrac{1}{2}\right)^i \left(\frac{\mu_q}{N\mu_H + \mu_q} \right) \right\} \right], \tag{27}$$

and consequently, the unconditional probability of an HAP handover request failure is given by:

$$P_{drop} = P_{loss} + (1 - P_{loss}) P_{fhA} . \tag{28}$$

4.3. Carried traffic and channel utilisation

Usually, channels of the cell are assigned for service requests in such a way that each channel receives, on the average, an equal fraction of the traffic load over the time period. For the reserved channels to provide certain level of priority, only a certain number is reserved not specific channels. The carried traffic by the HAP cell, A_c , is defined as the mean number of busy channels in the cell. Under statistical equilibrium, it is given by:

$$A_c = \sum_{j=1}^{N} j \; P_j = \lambda_c \; \overline{T}_H \; . \qquad (29)$$

The channel utilisation of the cell refers to the fraction of time during which the channel is occupied by a call:

$$\rho = A_c \,/\, N \qquad (30)$$

4.4. Average idle period and idle channels

A randomly chosen channel is usually either occupied by a call for an average duration of $\overline{T}_H = {\mu_H}^{-1}$ or being idle for an average duration of $\overline{T}_{idle} = {\mu_{idle}}^{-1}$. The channel utilisation can, then, be rewritten as:

$$\rho \; = \overline{T}_H \left[\overline{T}_H + \overline{T}_{idle} \right]^{-1} \; , \qquad (31)$$

and consequently, the average period during which the channel remains idle is given by:

$$\overline{T}_{idle} = \frac{1-\rho}{\rho} \times \overline{T}_H \; . \qquad (32)$$

In addition, as A_c represents the average number of busy channels in the cell, we can determine the average number of idle channels in the cell, N_{idle} , as:

$$N_{idle} = N - A_c \, . \qquad (33)$$

5. Numerical results and discussion

In this section, numerical results are presented for a sample case of a two-layer terrestrial/stratospheric hierarchical network. Each HAP cell is allocated 20 channels. We let the number of reserved handover channels to be N_h=0 and 1 while allowing the number of restricted channels NA=0 and 1. Consequently, we study three cases: case (a): N_A=0 & N_h=0; case (b): N_A=0 & N_h=1; case (c): N_A=1 & N_h=1. We will first introduce a set of results showing the network performance from the user's point of view and directly reflects user's satisfaction. The variation of the blocking probability of newly originated calls that overflow to the HAP is shown in fig. 4 as a function of the new call rate attempted per user category per cell. The corresponding blocking probability of those called placed by HAP-only users is depicted in fig. 5. In general, restricting the access of dual mode users and privileging HAP-only users with access to an extra channel improves the blocking probability for those calls that have primary access to the HAP cell. The increase in the blocking probability due to reserving a single channel for handover attempts is infinitesimally small as depicted in figs. 4 and 5, while the handover failure probability decreases significantly. This can be noticed in figs. 6 and 7 where the handover failure probabilities for overflow terrestrial handover attempts and HAP handover requests are displayed, respectively. This is an important performance metric as the user may accept access denying but the interruption of the call in progress is annoying and frustrating. Furthermore, introducing a queue for the HAP handover requests greatly improves the grade of service as can be seen when comparing fig. 6 and fig. 7.

Another set of performance measures that is more important from the network provider's point of view is the teletraffic handling capability as this will relate directly to his profit. The channel utilization which refers to the fraction of time during which the channel being busy is displayed in fig. 8 for different values of the call rate. The channel utilization

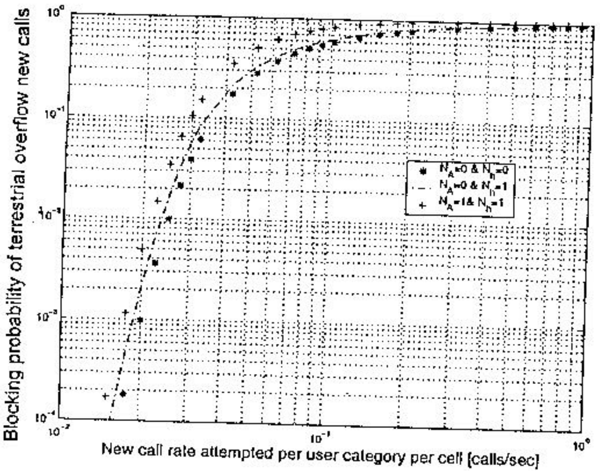

Fig. 4. Blocking probability of terrestrial overflow new alls.

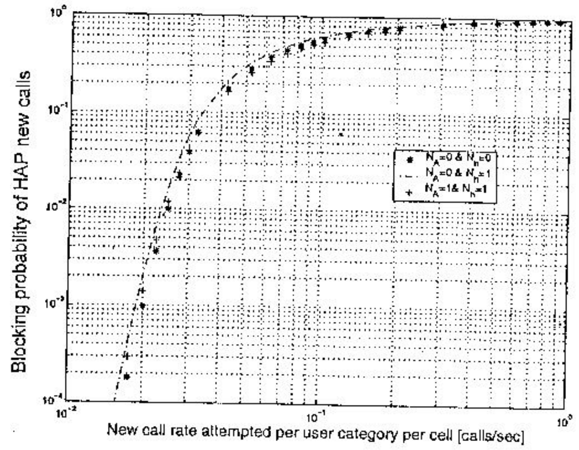

Fig. 5. Blocking probability of HAP new calls.

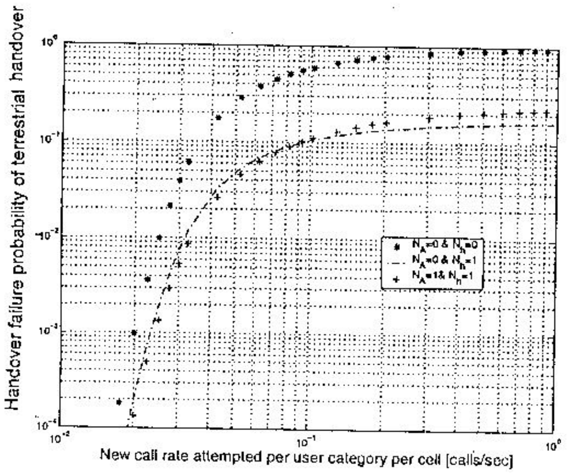

Fig. 6. Handover failure probability of terrestrial handover.

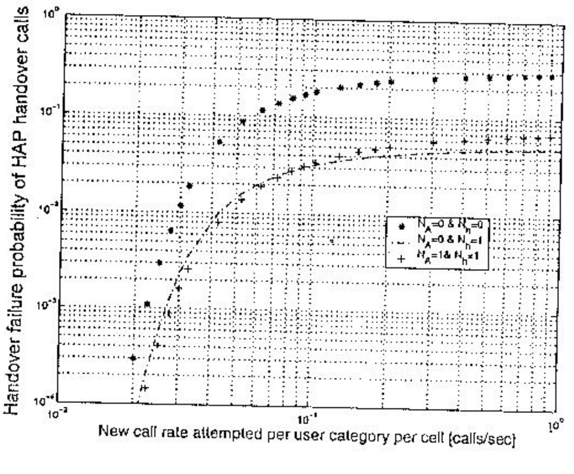

Fig. 7. Handover failure probability of HAP handover calls.

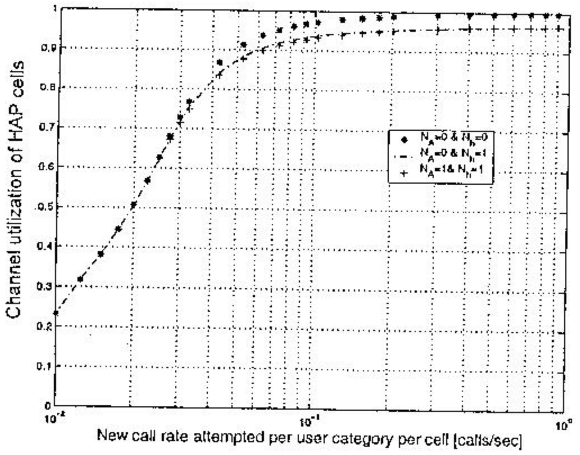

Fig. 8. Channel utilization of HAP cells.

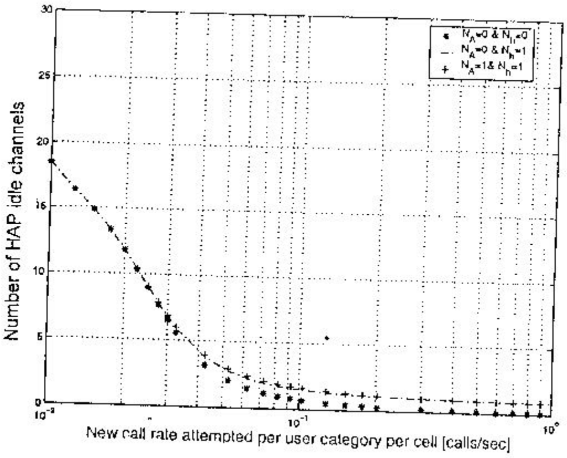

Fig. 9. Number of HAP idle channels.

gives also indication of the carried traffic per channel. Reserving channel for handover requests results in less channel utilization. Although increasing channel utilization is desirable from the service provider's view point, reserving channels for handover requests is a necessity for user satisfaction. The number of idle (not used) channels is shown in fig. 9. Increasing the network load results in more channel utilization, more carried traffic and less idle channels. Unfortunately, increasing the network load will also result in higher blocking and handover failure probabilities. The aim of teletraffic analysis is to estimate a trade off between user's satisfaction and network provider' view point.

6. Conclusions

An analytical model has been developed and used to analyze the overflow process of new calls and handover calls in a multilayer terrestrial/high altitude platform cellular network. Performance characteristics for users with different motilities are evaluated. With the use of multiple hierarchical overlays, the system performance is enhanced. The resultant system is robust with wide coverage areas, high channel capacity, and has inherent load-balancing and mobility-management capabilities.

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