Traffic model and performance evaluation of handling voice and data over multilayer cellular radio network

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The concept of a multilayer hierarchical cellular structure is explored for handling voice and data teletraffic in a wide area mobile radio network. At the microcells in the first layer, special attention is paid to handoff calls through channel reservation. The second layer is a macrocell that overlaid a number of microcells. More attention is devoted to handoff voice call and data session through reservation and queuing at the macrocell layer. The mathematical analysis of the proposed structure is presented and its performance is evaluated in terms of the blocking probability and the handoff failure probability of both voice and data traffic at the end of each layer.

لقد تضاعف فى الأونة الأخيرة عدد مشتركي الهاتف المحمول نظرا لما يقدمه من خدمات متميزة تزيد في أهميتها عن التليفون السلكي الثابت. و لذلك أصبح من الضروري حل أي مشكلة تعوق انتشار هذه الخدمة. أهم مشكلتين ظهرتا مؤخرا هما ازدحام قنوات الاتصال فى حالات الذروة فى المناطق الأهلة بالسكان مما يؤدى إلى فقد عدد من المكالمات، و عدم وصول الخدمة للأماكن ذات الكثافة السكانية المتوسطة مثل الريف و بعض المدن الجديدة و الصحارى .فى هذا البحث تم حل هاتين المشكلتين بتقسيم شبكة الاتصالات إلى طبقتين. الطبقة الأولى و تتكون من عدد من الخلايا الصغيرة الحجم و التي تناسب المناطق المزدحمة بالسكان، و الطبقة الثانية عبارة عن خلايا ذات حجم أكبر تغطى كل منها عدد من الخلايا الصغيرة بالإضافة إلى المساحات ذات الكثافة السكانية المتوسطة. من خلال هذا التقسيم يمكن ضمان توفير خدمة الهاتف المحمول لمساحات جديدة لم تكن متمتعة بهذه الخدمة من قبل بالإضافة إلى تقليل الفاقد فى مكالمات الخلايا الصغيرة الحجم عن طريق الحصول على قنوات اتصال جديدة من الخلايا الكبيرة الحجم. فى هذا البحث تم بناء نموذج لتمثيل هاتين الطبقتين، و تم التحليل الرياضي لهذا النموذج بحيث يراعى فيه (١) عدد المشتركين فى الخلايا الصغيرة و الكبيرة الحجم، (٢) إمكانية إرسال الصوت و البيانات فى آن واحد، (٣) تمييز مكالمات المناولة من خلية لأخرى، (٤) ضمان وصول الرسائل البيانية بنسبة ١٠٠%. تم تقييم أداء النظام المقترح بتحديد احتمالية الفقد فى المكالمات و البيانات الجديدة، حساب احتمالية الفقد فى مكالمات المناولة و تحديد احتمالية نقل البيانات من خلية للأخرى. النموذج المقترح يعتبر نموذج متكامل يمكن تطبيقه على شبكات الجيل الثالث لنظم الاتصالات المتحركة و النتائج التى حصلنا عليها تعتبر قاعدة بيانات توائم أى شبكة بأى حجم و أى عدد من المشتركين.

Key words: Traffic theory, Mobile communications, Multilayer modeling

1. Introduction

Third generation systems may include more than one layer to accommodate traffic generated from users with different densities in different cell sizes [1-3]. The concept of multilayer cellular systems appears to be a logical extension of the cellular system. Densely populated areas are more suitable to be covered by microcells that form the first layer, while the macrocells (i.e., layer 2) provide a continuous coverage of the service area. The macrocells work as a backup to handle overflow traffic from microcells in addition to serving users dispersed in zones without adequate coverage by microcells. However, working with microcells results in an unbounded handover. The interruption of a call in progress is annoying and frustrating to the users. So, special attention has to be paid to handoff attempts on designing a multilayer cellular system [4-7].

An efficient design for hierarchical cellular structure is still an open research issue. An adaptive overflow policy is required as well as a provision of uniform Grade of Service (GoS) between layers. The current paper aims at designing a more realistic multilayer cellular system considering the number of users in each layer and handling new and handoff voice and data traffic between layers. A priority is given to handoff attempts at both layers. The GoS is measured in terms of the blocking and dropping probabilities of voice and data traffic at each layer. The effect of overflow traffic is taken into consideration.

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The remainder of this paper is structured as follows: section 2 gives a general view of the multilayer architecture model. The analytical analysis of the proposed model is carried out in section 3. The results and its discussion are drawn in section 4. The paper is concluded in section 5.

2. Multilayer model architecture

The proposed architecture of the multilayer cellular structure is composed of two layers. The first layer includes a number of microcells, which overlaid by an umbrella macrocell representing the second layer. Each microcell and macrocell has its own base station, namely BS_1 and BS_2 respectively, see fig. 1. The offered traffic to the base station of a microcell depends on the number of users per microcell and the mobility of each user. The microcell is allocated a fixed number of channels, N_1. Each BS_1 is supposed to provide service to new voice calls, handoff voice calls, and new data session and handoff data session. The new voice calls, the new data session and the handoff data session are served by one of the $(N_1\text{-}v_1)$ channels. For each microcell, there is a number of channels, v_1 are being reserved exclusively for handoff voice calls between microcells. When all the N_1 channels in a microcell are busy, there are four types of traffic transferred to the macrocell, these are: 1) blocked new voice calls, 2)blocked new data session, 3)blocked handoff voice calls, and 4) blocked handoff data session.

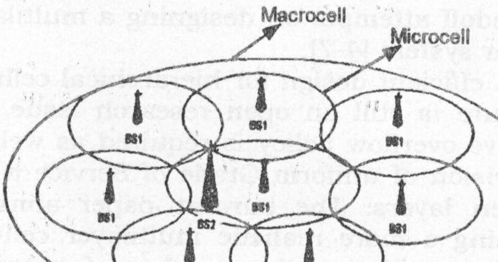

Fig. 1. Two layer architecture model.

In addition to the transferred traffic to the macrocell, it has its own traffic which consists of new voice calls, new data session, blocked handoff voice calls, and blocked handoff data session, see fig. 2. At this layer, priority is given to both handoff voice calls, and handoff data session through the reservation of v_2 and d_2 channels out of the N_2 channels for handoff voice and data traffic respectively. If the handoff attempt (voice or data) finds all the channels occupied, it can be queued for a limited time, which is the time elapsed through the handoff area between two macrocells. At the end of this time, the handoff voice attempt is blocked if it could not get a free channel. Because of the welling desire for the continuation of handoff data session, it will be transferred to the next macrocell if the queuing time is expired without getting a free channel.

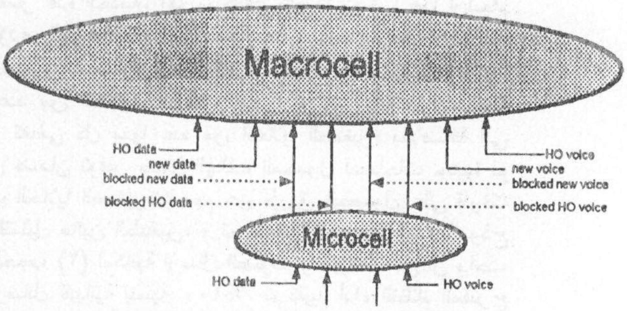

Fig. 2. Traffic arrival rate at each layer.

3. Analytical model

The following analytical model considers both the microcell layer and the macrocell layer. The performance measurements at the microcell layer is carried out by calculating the blocking probability of both new voice calls and new data session and the handoff failure probability of handed off voice calls and data session. At the macrocell layer the blocking probability of voice calls and data session, the dropping probability of handed off voice calls, and the transfer probability of data session to the next macrocell layer are calculated.

3.1. The microcell layer

The microcells are generally characterized by small size, so the number of users can be statistically defined. On dealing with a finite number of users with respect to the number of connections already in service, a more realistic approach is adopted through analyzing the teletraffic model in this layer by Engset formula [8]. We assume that the traffic offered to any of the microcells is symmetrical, so the analysis is focused on one of these micorcells. Each microcell in this layer has its own fixed number of channels, N_1. Handoff voice calls are privileged with reserving v_1 channels out of the N_1 channels. We consider that the microcell is of circular shape with radius R_m. The new voice and data call origination rate in a microcell are denoted as λ_{nv1} and λ_{nd1} respectively, and are given by:

$$\lambda_{nv1}(j) = \alpha(M_u - j)\lambda_{iv1}, \tag{1}$$

$$\lambda_{nd1}(j) = \beta(M_u - j)\lambda_{id1}, \tag{2}$$

where α denotes the fraction of M_u users that generate voice calls and $\beta = (1-\alpha)$ denotes the fraction of M_u users that generates data sessions. The number of users M_u is related to the user density D_u as $M_u = \pi R^2 D_u$. The call arrival rate per user per unit area for both voice and data are given by λ_{iv1} and λ_{id1}, respectively.

3.1.1. Channel holding time in a microcell

The channel holding time of a new voice call originated in a microcell, T_{Hiv1}, is either the total call duration, T_{Mv1}, of a mobile user that completes the call within the microcell, or the time, T_{n1}, spent in the microcell by the mobile user from the beginning of the call until he is handed over to the next microcell, whichever is least [9]. Then T_{Hiv1} is given by:

$$T_{Hiv1} = \min(T_{Mv1}, T_{n1}), \tag{3}$$

and consequently the CDF of T_{Hiv1} is

$$F_{T_{Hiv1}}(t) = F_{T_{Mv1}} + F_{T_{n1}}(1 - F_{T_{Mv1}}(t)). \tag{4}$$

The channel holding time of a handoff voice call, T_{Hhv1} is either the remaining message duration T_{Mv1} or the mobile user residing time T_{h1} in the cell, whichever is least. Then:

$$T_{Hhv1} = \min(T_{Mv1}, T_{h1}). \tag{5}$$

The CDF of T_{Hhv1} is,

$$F_{T_{Hhv1}}(t) = F_{T_{Mv1}}(t) + F_{T_{h1}}(t)(1 - F_{T_{Mv1}}(t)). \tag{6}$$

In a similar approach the CDF of the channel holding time of new data session $F_{T_{Hid1}}(t)$ and handoff data session $F_{T_{Hhd1}}(t)$ are given by :

$$F_{T_{Hid1}}(t) = F_{T_{Md1}}(t) + F_{T_{n1}}(t)(1 - F_{T_{Md1}}(t)), \tag{7}$$

$$F_{T_{Hhd1}}(t) = F_{T_{Md1}}(t) + F_{T_{h1}}(t)(1 - F_{T_{Md1}}(t)). \tag{8}$$

Assume that $T_{Mv1}, T_{Md1}, T_{n1}, T_{h1}$ are independent negatively exponentially distributed random variables with mean values of;

$$\bar{T}_{Mv1} = 1/\mu_{Mv1}, \bar{T}_{Md1} = 1/\mu_{Md1},$$

$$\bar{T}_{n1} = 1/\mu_{n1}, \bar{T}_{h1} = 1/\mu_{h1}.$$

The CDF of the average channel holding time $F_{T_{H1}}(t)$ in a microcell is given by:

$$F_{T_{H1}}(t) = \frac{1}{\lambda_{m1}}\Big[\lambda_{nv1}(1 - P_{Bv1})F_{T_{Hiv1}}(t) + \lambda_{hv1}(1 - P_{fhv1})F_{T_{Hhv1}}(t) + \lambda_{nd1}(1 - P_{Bd1})F_{T_{Hid1}}(t) + \lambda_{hd1}(1 - P_{fhd1}))F_{T_{Hhd1}}(t)\Big]$$

where:

$$\lambda_{m1} = \lambda_{nv1}(1 - P_{Bv1}) + \lambda_{hv1}(1 - P_{fhv1}) + \lambda_{nd1}(1 - P_{Bd1}) + \lambda_{hd1}(1 - P_{fhd1}). \tag{9}$$

Where P_{Bv1} and P_{fhv1} are the blocking probability, handoff failure probability of new and handoff voice calls respectively. The probabilities P_{Bd1} and P_{fhd1} are the blocking probability, handoff failure probability of new and handoff data session respectively. The probability density function $f_{T_{H1}}(t)$ of the channel holding time is given by differentiating the CDF value. The mean value of $f_{T_{H1}}(t)$ is given by:

$$\bar{T}_{H_1} = \int_0^t t f_{T_{H1}}(t)dt$$

$$= \frac{1}{\lambda_{m1}}\left[\frac{\lambda_{nv1}(1-P_{Bv1})}{\mu_{Mv1}+\mu_{n1}} + \frac{\lambda_{hv1}(1-P_{fhv1})}{\mu_{Mv1}+\mu_{h1}} + \frac{\lambda_{nd1}(1-P_{Bd1})}{\mu_{Md1}+\mu_{n1}} + \frac{\lambda_{hd1}(1-P_{fhd1})}{\mu_{Md1}+\mu_{h1}}\right]. \quad (10)$$

Let P_{nv1} denote the probability that a successfully established new voice call may need handover before completion, and P_{hv1} represent the probability that a successfully handover voice call may need further handover before completion. These are given by:

$$P_{nv1} = P_r\{T_{n1} \succ T_{Mv1}\} = \int_0^\infty \left[1 - F_{T_{Mv1}}(t)\right] f_{T_{n1}}(t)dt$$

$$= \int_0^\infty e^{-\mu_{Mv1}} f_{T_{n1}}(t)dt = \frac{\mu_{n1}}{\mu_{Mv1}+\mu_{n1}}, \quad (11)$$

$$P_{hv1} = P_r\{T_{h1} \succ T_{Mv1}\} = \int_0^\infty \left[1 - F_{T_{Mv1}}(t)\right] f_{T_{h1}}(t)dt$$

$$= \int_0^\infty e^{-\mu_{Mv1}} f_{T_{n1}}(t)dt = \frac{\mu_{h1}}{\mu_{Mv1}+\mu_{h1}}, \quad (12)$$

The handoff rate of voice call λ_{hv1} in a microcell is given by:

$$\begin{aligned}\lambda_{hv1} &= \lambda_{nv1}(1-P_{Bv1})P_{nv1} \\ &\quad + \lambda_{nv1}(1-P_{Bv1})P_{nv1}\left[(1-P_{fhv1})P_{hv1}\right] \\ &\quad + \lambda_{nv1}(1-P_{Bv1})P_{nv1}\left[(1-P_{fhv1})P_{hv1}\right] \\ &\quad \left[(1-P_{fhv1})P_{hv1}\right] + \ldots \\ &= \frac{\lambda_{nv1}(1-P_{Bv1})P_{nv1}}{1-(1-P_{fhv1})P_{hv1}}. \quad (13)\end{aligned}$$

In a similar way, the handoff rate of data session in a microcell is,

$$\lambda_{hd1} = \frac{\lambda_{nd1}(1-P_{Bd1})P_{nd1}}{1-(1-P_{fhd1})P_{hd1}}. \quad (14)$$

Where P_{nd1} is the probability that a successfully established data session may need handover before completion, and P_{hd1} is the probability that a successfully handover data session may need further handover before completion.

3.1.2. Performance evaluation of the microcell layer

Let j denote the number of connections being handled by BS₁. The state probability P_j of BS₁ is

$$P_j = \begin{cases} \binom{M_u}{j}\left[(\lambda_{iv1}+\lambda_{hv1})+(\lambda_{id1}+\lambda_{hd1})\right]^j \times \\ P_0/\mu_{H_1}{}^j \ldots 0 \le j \le N_1 - v_1 \\ \binom{M_u}{j}\left[\left[(\lambda_{iv1}+\lambda_{hv1})+(\lambda_{id1}+\lambda_{hd1})\right]^{(N_1-v_1)}\lambda_{hv1}{}^{j-(N_1-v_1)}\right] \\ \times P_0/\mu_{H_1}{}^j \ldots (N_1-v_1)+1 \le j \le N_1, \end{cases} \quad (15)$$

where $\mu_{H_1} = 1/\bar{T}_{H_1}$ and $\bar{T}_{H_1}$ is the average channel holding time and P_0 is the probability of BS₁ being idle, i.e.,

$$P_0{}^{-1} = \sum_{k=1}^{N_1-v_1}\binom{M_u}{k}\frac{\left[(\lambda_{iv1}+\lambda_{hv1})+(\lambda_{id1}+\lambda_{hd1})\right]^k}{\mu_{H_1}{}^k} + \sum_{k=N_1-v_1+1}^{N_1}\binom{M_u}{k}\times \frac{\left[(\lambda_{iv1}+\lambda_{hv1})+(\lambda_{id1}+\lambda_{hd1})\right]^{N_1-v_1}\lambda_{hv1}{}^{k-(N_1-v_1)}}{\mu_{H_1}{}^k}.$$

The blocking probability of new voice calls is,

$$P_{Bv1} = \sum_{j=N_1-v_1}^{N_1}\binom{M_u-1}{j}\left[(\lambda_{iv1}+\lambda_{id1})+(\lambda_{id1}+\lambda_{hd1})\right]^{N_1-v_1}\times \lambda_{hv1}{}^{j-(N_1-v_1)}P_0/\mu_{H_1}{}^j. \quad (16)$$

The blocking probability of new data session, P_{Bd1} and handoff failure probability of data session, P_{fhd1} are equal to the blocking probability of new voice calls, i.e.,

$$P_{Bd1} = P_{fhd1} = P_{Bv1} \ . \qquad (17)$$

The handoff failure probability of a handoff voice call in a microcell P_{fhv1} when all the N_1 channels are busy is,

$$P_{fhv1} = \binom{M_u - 1}{N_1} \frac{\left[(\lambda_{iv1} + \lambda_{hv1}) + (\lambda_{id1} + \lambda_{hd1}\right]^{N_1 - v_1} \lambda_{iv1}{}^{v_1}}{\mu_{H_1}{}^{N_1}} P_0 \ . \qquad (18)$$

The transferred traffic to the macrocell layer consists of:

1. blocked new voice call rate, viz.,

$$\lambda_{Miv2} = \sum^{m} \lambda_{nv1} P_{Bv1} \ , \qquad (19)$$

where m is the number of microcells overlaid by a macrocell,

2. the rate of handoff failure of voice calls, i.e.,

$$\lambda_{Mhv2} = \sum^{m} \lambda_{hv1} P_{fhv1} \ , \qquad (20)$$

3. the rate of blocked new data session, which is

$$\lambda_{Mid2} = \sum^{m} \lambda_{nd1} P_{Bd1} \ , \qquad (21)$$

4. the rate of failure handoff data session which is,

$$\lambda_{Mhd2} = \sum^{m} \lambda_{hd1} P_{fhd1} \ . \qquad (22)$$

3.2. *The macrocell layer*

The macrocell is supposed to serve large number of users grouped from the covered number of microcells in addition to zones without adequate coverage by microcells. When the number of users is large compared to the number of channels at the macrocell, the calls are requested randomly and are independent of the number of busy users [9]. In this case Erlang's loss formula is more appropriate for handling traffic at this layer. The new call rate in a macrocell of circular shape and radius R_M is the aggregation of the new voice call arrival rate, λ_{nv2}, and the new data session arrival rate, λ_{nd2}, which are given by:

$$\lambda_{nv2} = \alpha M_M \lambda_{iv2} \ , \qquad (23)$$

$$\lambda_{nd2} = \beta M_M \lambda_{id2} \ , \qquad (24)$$

where the number of users in a macrocell M_M is related to the user density D_M as $M_M = \pi R_M^2 D_M$. Throughout the macrocell layer, the handoff voice calls will refer to both of handoff voice calls between macrocells and blocked handoff voice calls transferred from miceocells, and so is the case with data session. Also, new voice calls at macrocell will refer to both of new voice calls originated at the macrocell and the blocked voice calls transferred from microcells, and so is the case with session.

3.2.1. *Channel holding time in a macrocell*

In a similar manner to that followed in a microcell layer, the CDF of the channel holding time in this layer is,

$$F_{T_{H2}}(t) = \frac{1}{\lambda_{M2}} \left\{ \begin{array}{l} \left[(\lambda_{nv2} + \lambda_{Miv2})(1 - P_{Bv2})\right] F_{T_{H_{iv2}}}(t) \\ + \left[(\lambda_{hv2} + \lambda_{Mhv2})(1 - P_{fhv2})\right] F_{T_{H_{hv2}}} \\ + \left[(\lambda_{nd2} + \lambda_{Mid2})(1 - P_{Bd2})\right] F_{T_{H_{id2}}} \\ + \left[(\lambda_{hd2} + \lambda_{Mhd2})(1 - P_{thd2})\right] F_{T_{H_{hd2}}} \end{array} \right\} . \qquad (25)$$

where,

$$\lambda_{M2} = (\lambda_{nv2} + \lambda_{Miv2})(1 - P_{Bv2}) + (\lambda_{hv2} + \lambda_{Mhv2})(1 - P_{fhv2}) + (\lambda_{nd2} + \lambda_{Mid2})(1 - P_{Bd2}) + (\lambda_{hd2} + \lambda_{Mhd2})(1 - P_{thd2}) .$$

The average value of the channel holding time is,

$$\bar{T}_{H_2} = \frac{1}{\lambda_{M2}} \left[\begin{array}{l} \dfrac{(\lambda_{nv2} + \lambda_{Miv2})(1 - P_{Bv2})}{\mu_{Mv2} + \mu_{n2}} + \dfrac{(\lambda_{hv2} + \lambda_{Mhv2})(1 - P_{fhv2})}{\mu_{Mv2} + \mu_{h2}} \\ + \dfrac{(\lambda_{nd2} + \lambda_{Mid2})(1 - P_{Bd2})}{\mu_{Md2} + \mu_{n2}} + \dfrac{(\lambda_{hd2} + \lambda_{Mhd2})(1 - P_{thd2})}{\mu_{Md2} + \mu_{h2}} \end{array} \right] . \qquad (26)$$

The handoff rate of voice call and data session are given by:

$$\lambda_{hv2} = \frac{(\lambda_{nv2} + \lambda_{Miv2})(1 - P_{Bv2})P_{nv2}}{1 - (1 - P_{fhv2})P_{hv2}}, \quad (27)$$

$$\lambda_{hd2} = \frac{(\lambda_{nd2} + \lambda_{Mid2})(1 - P_{Bd2})P_{nd2}}{1 - (1 - P_{thd2})P_{hd2}}. \quad (28)$$

3.2.2. Performance evaluation of the macrocell layer

To calculate the steady state probability P_j of a macrocell base station let,

$$A_1 = (\lambda_{nv2} + \lambda_{Miv2}) + (\lambda_{hv2} + \lambda_{Mhv2}) + (\lambda_{nd2} + \lambda_{Mid2}) + (\lambda_{hd2} + \lambda_{Mhd2}),$$

$$A_2 = (\lambda_{hv2} + \lambda_{Mhv2}),$$

$$A_3 = (\lambda_{hd2} + \lambda_{Mhd2}),$$

$$A_4 = (\lambda_{hv2} + \lambda_{Mhv2}) + (\lambda_{hd2} + \lambda_{Mhd2}).$$

Then P_j is given by:

$$P_j = \begin{cases} \dfrac{A_1^{\,j}}{j!\,\mu_{H_2}{}^{j}} P_0 \ldots 1 \le j \le N_2 - v_2 - d_2, \\[2ex] \dfrac{A_1^{\,N_2-v_2-d_2} A_2^{\,j-(N_2-v_2-d_2)}}{j!\,\mu_{H_2}{}^{J}} p_0 \ldots (N_2 - v_2 - d_2) + 1 \le j \le N_2 - d_2, \\[2ex] \dfrac{A_1^{\,N_2-v_2-d_2} A_2^{\,v_2} A_3^{\,j-(N_2-d_2)}}{j!\,\mu_{H_2}{}^{j}} P_0 \ldots (N_2 - d_2) + 1 \le j \le N_2, \\[2ex] \dfrac{A_1^{\,N_2-v_2-d_2} A_2^{\,v_2} A_3^{\,d_2} A_4^{\,j-N_2}}{N_2!\,\mu_{H_2}{}^{N_2} \prod_{i=1}^{j-N_2} (N_2 \mu_{H_2} + i\mu_Q)} P_0 \ldots j \ge N_2. \end{cases} \quad (29)$$

where $\bar{T}_Q = 1/\mu_Q$ is the average queue time in the macrocell handoff area, and P_0 is equal to:

$$P_0^{-1} = \sum_{k=1}^{N_2-v_2-d_2} \frac{A_1^{\,k}}{k!\,\mu_{H_2}{}^{k}} + \sum_{k=N_2-v_2-d_2+1}^{N_2-d_2} \frac{A_1^{\,N_2-v_2-d_2} A_2^{\,K-(N_2-v_2-d_2)}}{k!\,\mu_{H_2}{}^{k}} + \sum_{k=N_2-d_2+1}^{N_2} \frac{A_1^{\,N_2-v_2-d} A_2^{\,v_2} A_3^{\,k-(N_2-d_2)}}{k!\,\mu_{H_2}{}^{K}} + \sum_{k=N_2+1}^{\infty} \frac{A_1^{\,N_2-v_2-d_2} A_2^{\,v_2} A_3^{\,d_2} A_4^{\,k-N_2}}{N_2!\,\mu_{H_2}{}^{N_2} \prod_{i=1}^{k-N_2} (N_2 \mu_{H_2} + i\mu_Q)}.$$

The blocking probability of voice calls is given by:

$$P_{Bv2} = \sum_{j=N_2-v_2-d_2}^{\infty} P_j \,. \quad (30)$$

The blocking probability of data session is equal by definition to the blocking probability of voice calls, i.e.

$$P_{Bd2} = P_{Bv2} \,. \quad (31)$$

When all the N_2 channels of the macrocell are busy, the queue will be the end state for both of handoff voice calls and data session. The probability that these attempts will enter the queue is given by:

$$P_q = \sum_{j=N_2}^{\infty} \frac{A_1^{\,N_2-v_2-d_2} A_2^{\,v_2} A_3^{\,d_2} A_4^{\,j-N_2}}{N_2!\,\mu_{H_2}{}^{N_2} \prod_{i=1}^{j-N_2} (N_2 \mu_{H_2} + i\mu_Q)} P_0 \,. \quad (32)$$

The average number of attempts in the queue is,

$$L_q = \sum_{j=N_2}^{\infty} (j - N_2) P_j \quad (33)$$

The average waiting time in the queue can be obtained from the well known Little's formula, which is given by:

$$L_q = W.\lambda_{fhmM}, \quad (34)$$

where λ_{fhmM} is the aggregate rate of failure handoff voice and data in the macrocell layers, which is given by:

$$\lambda_{fhmM} = P_{Bv2}(\lambda_{Mhv2} + \lambda_{hv2}) + P_{Bd2}(\lambda_{Mhd2} + \lambda_{hd2})$$

The conditional probability that a handover voice attempt that joined a queue at position i will succeed to get a channel before being dropped is given by [9]:

$$P_{sv} = \left[\frac{N_2 \mu_{H_2}}{N_2 \mu_{H_2} + \mu_Q}\right] \prod_{i=1}^{j-N_2} \left[1 - \left(\frac{\mu_Q}{N_2 \mu_{H_2} + \mu_Q}\right)\left(\frac{1}{2}\right)^{i}\right]. \quad (35)$$

The failure probability of a handover voice attempt, P_{fhv2} is given by:

$$P_{fhv2} = P_q(1 - P_{sv}) \; . \tag{36}$$

The probability that the queued handover data attempt will be transferred to the next macrocell is equal to the probability that it joined the queue but failed to get a free channel before the time $\bar{T_Q}$ is expired, then,

$$P_{thd2} = P_{fhv2} \; . \tag{37}$$

4. Results and discussion

For the multilayer cellular architecture model, two radii of the microcells are considered in order to study the effect of microcell length on the average rate of handoff voice and data between microcells, and so the average rate of transferred traffic to the macrocell. The two radii of the microcells are 250 and 500 m, respectively. For the two radii, ten microcells are overlaid by one macrocell of 2.5 km radius. The traffic offered to each microcell is served by 16 channels, while 32 channels are allocated for each macrocell. To study the effect of reservation on handoff voice calls, two cases are studied. The first is with reserving 2,3 and 4 channels in the microcell layer, while the second is in the macrocell layer with reserving 2,4 and 6 channels. For each microcell and macrocell, the user densities are100 and 40 user/km^2 respectively. For each of the microcells and macrocells, the average fraction of voice users is 0.7 and the average fraction of data users is 0.3. The speed of a mobile station is assumed to be uniformly distributed with maximum values of 40 and 120 km/h in the microcell and macrocell, respectively. The average voice call duration is 120 s, while it is 60 s for data session duration. The mean dwell time for the handoff voice and data attempts in the macrocell overlapping areas ($\bar{T}_Q = 1/\mu_Q$) is assumed equal to $\overline{T_{H_2}}/10$.

The first four figures are drawn with reserving four channels in the macrocell layer, two for handoff voice calls and another two for handoff data session.

Figs. 3 and 4 are drawn with microcell radius of 250 m. The effect of reserving 2 channels for handoff voice calls in each microcell is clear through the significant decrease of handoff failure probability shown in fig. 4, compared with no reservation in fig. 3. Figs. 5 and 6 are drawn with microcell radius of 500 m. The effect of decreasing the radius of microcells is obvious through the increase of the average call arrival rate of new and handoff calls in the microcell layer, while the corresponding one at the macrocell layer is nearly constant.

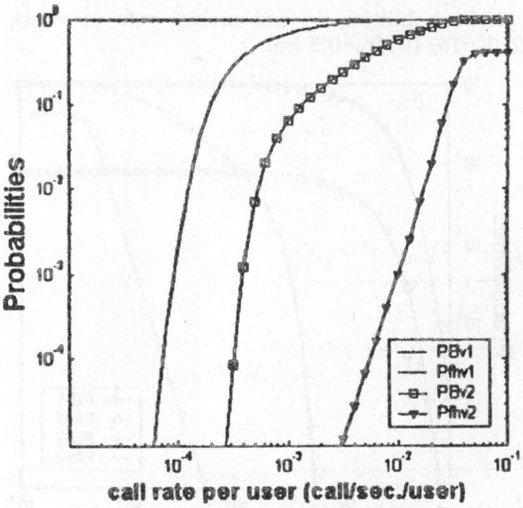

Fig. 3. Probabilities vs call arrival rate at v1=0, d2=2, v2=2, T_q=T_H/10, R_m=0.25 km.

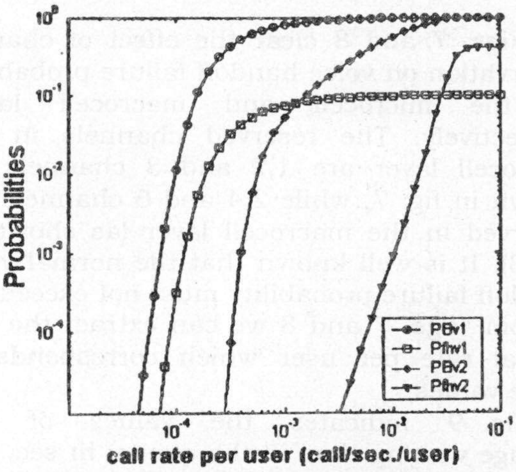

Fig. 4. Probabilities vs call arrival rate at v1=2, d2=2, v2=2, T_q=T_H/10, R_m=0.25 km.

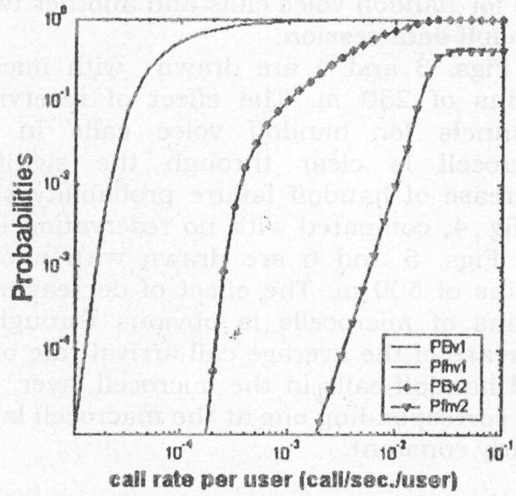

Fig. 5. Probabilities vs call arrival rate at v1=0, d2=2, v2=2, T_q=T_H/10, R_m=0.5 km.

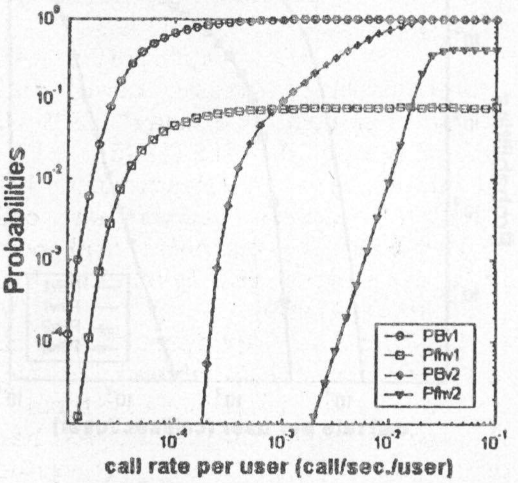

Fig. 6. Probabilities vs call arrival rate at v1=2, d2=2, v2=2, T_q=T_H/10, R_m=0.5 km.

Figs. 7 and 8 clear the effect of channel reservation on voice handoff failure probability in the microcell and macrocell layer, respectively. The reserved channels in the microcell layer are 1,2 and 3 channels (as shown in fig. 7, while 2,4 and 6 channels are reserved in the macrocell layer (as shown in fig. 8). It is well known that the normal voice handoff failure probability must not exceed 10^{-4}, from figs. 7 and 8 we can extract the call arrival rate per user which corresponds to these values.

Fig. 9 indicates the values of the average waiting time in the queue, in sec, (for voice and data) at v_1 =2 channels, v_2=2,3, and 4 channels, and R_m=0.5 Km. The curves of the

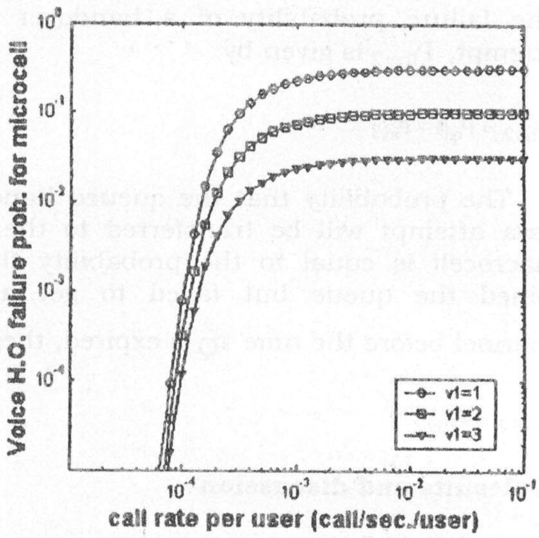

Fig. 7. Voice H.O failure prob. For microcell vs call arrival rate at v1=1, 2, 3, d2=2, v2=2, T_q=T_H/10, R_m=0.5 km.

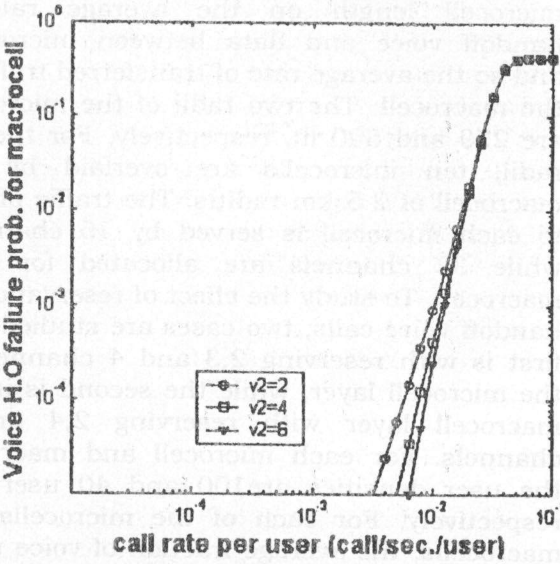

Fig. 8. Voice H.O failure prob. for macrocell vs call arrival rate at v1=2, d2=2, v2=2, 4, 6, T_q=T_H/10, R_m=0.5 km.

figure indicate the increase in the average waiting time with increasing the call rate per user and decreasing the reserved number of channels. There is abrupt decrease in the waiting time at certain point where $T_q = T_H/10$ where the queued voice calls will be dropped from the queue. At this point, only data messages will be waiting in the queue, and this is clear from the falling down part of the curve.

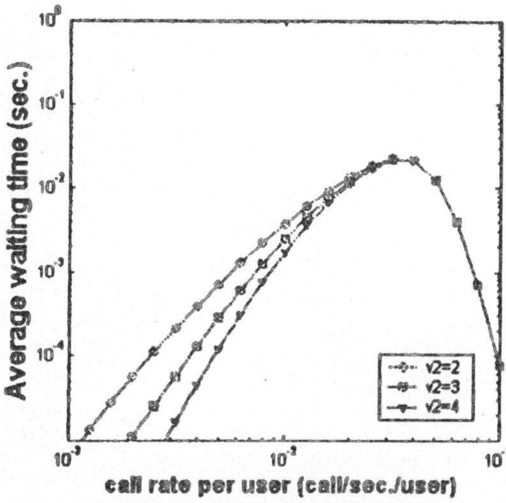

Fig. 9. Average waiting time vs call arrival rate at v2=2, 3, 4, d2=2, v1=2, $T_q=T_H/10$, R_m=0.5 km.

5. Conclusions

A traffic model and analysis of a hierarchically multilayer cellular radio network is considered. A more realistic approach that considered the number of users with respect to the number of channels in use in a microcell and macrocell is adopted. The model treated both voice and data and their relatives of handoffs in both layers. Handoffs are given priorities in order to improve the system performance. The analysis can be used as a tool to decide on the adoption of a particular overflow traffic management strategy.

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