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Channel-sharing strategies in two-tier cellular PCS systems

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Abstract

A *two-tier cellular network* is characterized by *macrocells* and *microcells* overlapping in the service area. This overlapping property provides an advantage that traffic loads can be shared by channels of the two tiers to increase the performance of the system. In this paper, we propose two channel-sharing strategies, namely *vertical channel-sharing* and *vertical–horizontal channel-sharing*, to better utilize channels of the network. The call loss probability of new calls and *call dropping probability* of handoff calls are developed through analyses and simulations. The results justify the advantage of our strategies over existing strategies. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Cellular network; Channel management; Load balance; Personal communication system; Two-tier cellular system

1. Introduction

The *personal communication system* (PCS) is one of the fastest growing industries recently. One inherent limitation to wireless communication is the scarce wireless bandwidth, which can never catch up with the increase of user demand. One way to relieve the stress is to use a two-tier cellular structure to increase *channel reuse* (or *frequency reuse*). Resident on the top layer are larger cells called *macrocells*, while resident on the bottom layer are smaller cells called *microcells*. Macrocells and microcells can overlap with each other in the service area. Such an arrangement is more dynamic than a single-tier system, and thus can offer a chance to optimize the performance of the system based on factors such as roaming speed of users, level of cloudiness of an area, location management, channel management, etc. Many works have been directed toward this direction [1–7]. In Refs. [1–3,7], subscribers are assigned to microcell or macrocell based on their mobility. In Ref. [5], calls are classified into several categories depending on their velocities; different handoff thresholds are used for them. It was proposed in Ref. [4] to direct call termination and paging on the same tier to reduce paging cost. The velocity threshold to choose tiers is dynamically selected in Ref. [6].

The main purpose of this paper is to investigate the possibility of sharing channels between the upper tier and lower tier in a two-tier system. This is very natural because mobile subscribers are likely to be covered by a macrocell and microcell, and thus they should be able to support each other when channels are stressed. The potential advantage is higher channel utilization, and the cost is at more handoffs. A number of works have addressed this issue. In Refs. [7,8], it is proposed to direct a new/handoff call to the appropriate tier based on its previous speed. However, when there are no available channels on the preferred tier, the call will be directed to the other (un-preferred) tier. This is called an *overflow*. In Ref. [9], only overflows from the low tier to the high tier are allowed, while in Ref. [10] overflows from the low tier to the high tier are restricted to only handoffs. In Ref. [11], mobile subscribers traveling on the low tier may borrow channels from a pool of reserved handoff channels provided by the high tier.

In Ref. [12], two-way overflows between both tiers are considered. Also, a *take-back* scheme is introduced so as to redirect a call from an un-preferred tier to a preferred tier at the occasions of handoffs. That is, whenever possible, a fast subscriber overflowed to a microcell will be taken back to a macrocell when it crosses any microcell boundary, and vice versa for a slow subscriber. Observing that two continuous cells usually have some overlapping on their radio coverage areas, Marano et al. [13] proposes a *channel rearrangement* scheme by forcing a handset in the overlapping area to take an *early handoff* prematurely, if the signal quality in the next cell is acceptable. This will vacate a channel in the previous cell. A chaining effect may even take place if this causes a sequence of subscribers to take early *handoffs*.

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Table 1
Comparisons of channel-sharing strategies on the number of ways to redirect a call

Methods	Strategies	Number of redirecting directions
[7,8]	Handoff	0
[9,10]	Overflow (one-way)	1
[11]	Borrow	1
[12]	Overflow (two-way)	1
[13]	Rearrange + overflow	$v + 1$
This work	Vertical	n
This work	Vertical–horizontal	$n + v$

The above reviews have shown the flexibility of two-tier systems in transferring the load to overlapping and neighboring cells. In this paper, we investigate the possibility of exploiting more flexibilities of sharing channels in such a two-tier environment. We propose a new strategy called *vertical channel-sharing*. When a macrocell or a microcell is short of channels, multiple cells can be involved to resolve this problem. The potential advantage is higher channel utilization. More specifically, suppose that a macrocell is overlapping with n microcells. When a channel request arrives at the macrocell, if the macrocell has no free channels, we can either overflow this call to its corresponding microcell, or force one of the calls on the macrocell to move to one of the other $n - 1$ overlapping microcells to vacate a channel on the macrocell. On the contrary, when a channel request arrives at a microcell, if the microcell has no free channels, we can either overflow this call to the macrocell, or force one of the calls on the macrocell to move to one of the other $n - 1$ overlapping microcells to vacate a channel on the macrocell. Then the new call can be overflowed to the macrocell. We observe that such channel-sharing provides a lot of flexibilities to shift the load among the cells on the two tiers. In comparison, existing works only consider a simple overflow from one tier to another tier; the possibility of shifting the load to the neighboring $n - 1$ microcells is not explored.

On top of the vertical channel-sharing strategy, we further propose a *vertical–horizontal channel sharing* strategy. The basic idea is to combine the earlier vertical channel-sharing with the channel rearrangement strategy in Ref. [13], where calls are allowed to take early handoffs on the higher tier (in horizontal direction) when the system is in channel shortage.

A summary on the numbers of ways to shift a channel request by other schemes and ours is in Table 1. This shows the flexibility of our strategies. Note that n is the number of microcells covered by a macrocell, and v is the number of macrocells neighboring to each macrocell. Formal analyses are provided to evaluate the performance of our vertical and vertical–horizontal channel-sharing strategies. Simulation results are also provided to verify our analyses. The results do justify the benefits of using our strategies.

The rest of this paper is organized as follows. Our channel-sharing strategies are described in Section 2. Call loss probability of new calls is derived in Section 3. Comparisons, including numerical and simulation results, are presented in Section 4. Section 5 concludes this paper.

2. Vertical and horizontal channel-sharing strategies

In the following discussion, we will consider a macrocell M, which overlaps with n microcells $m_1, m_2,\ldots,m_n$, and neighbors to v macrocells $M_1, M_2,\ldots,M_v$. Suppose that there is a channel request arriving at the macrocell M or one of n microcells $m_1, m_2,\ldots,m_n$. If there is no channel in the cell to satisfy this request, our *vertical channel-sharing* strategy or our *vertical–horizontal channel*-sharing strategy will take place, trying to find a channel to serve this request.

The vertical channel-sharing strategy tries to find a channel by shifting calls in the vertical direction, i.e. from one tier to the other tier. The vertical–horizontal channel-sharing strategy tries to find a channel by shifting calls in the vertical direction first. If this fails, it will try to shift calls in the horizontal direction on the higher tier. In Sections 2.1 and 2.2, we will discuss channel sharing in vertical and

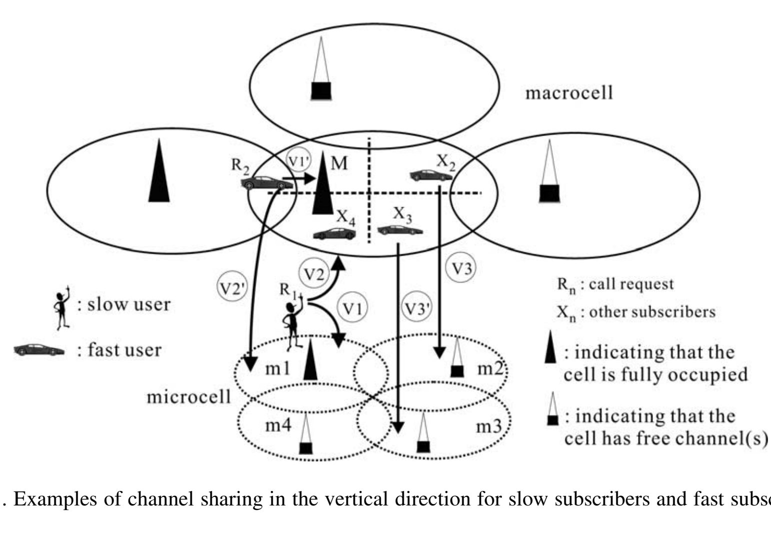

Fig. 1. Examples of channel sharing in the vertical direction for slow subscribers and fast subscribers.

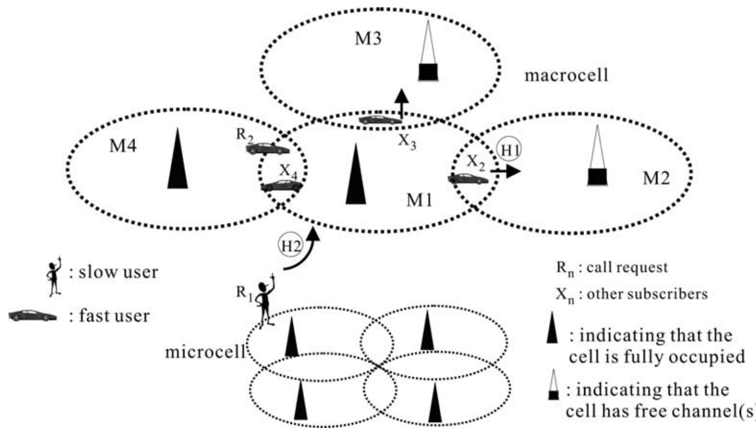

Fig. 2. Examples of channel sharing in the horizontal direction for slow subscribers and fast subscribers.

horizontal directions. Section 2.1 is for the first strategy, while the combination of Sections 2.1 and 2.2 is for the second strategy.

2.1. Channel sharing in the vertical direction

By 'vertical', we mean transferring calls between the two tiers. In the following, we separate our discussion into calls arriving at the low tier and at the high tier. When there is a channel request to microcell m_i, $1 \le i \le n$, the following steps will be executed:

V1. If there is a free channel in m_i, assign this channel to the request.
V2. Otherwise, 'overflow' the request to the macrocell M if there is a free channel in M.
V3. Otherwise, pick any call in M such that the call's corresponding microcell, say m_j, has a free channel. Transfer the call to m_j to vacate a channel in M, and then 'overflow' the channel request to M.

For example, in Fig. 1, a slow subscriber R_1 arrives at microcell m_1,which has no free channel. By V2, R_1 will be overflowed to macrocell M. Since M is also full, the strategy will try to identify a user which is currently served in macrocell M and which can be handoff to a microcell with a free channel. In this example, user X_2 can be shifted to a channel in microcell m_2. After doing so, the channel released by X_2 in the high tier can be used by R_1.

When there is a channel request to M, the following steps will be executed:

V1′. If there is a free channel in M, assign this channel to the request.
V2′. Otherwise, 'overflow' this request to its corresponding microcell if the microcell has a free channel.
V3′. Otherwise, pick any call in M such that the call's corresponding microcell, say m_j, has a free channel. Transfer the call to m_j to vacate a channel in M, and then assign the vacated channel to the request.

For example, in Fig. 1, a fast subscriber R_2 moves into macrocell M, which has no free channel. Then step V2′ will first try to overflow R_2 to its corresponding microcell m_1. Since m_1 is full too, step V3′ will try to locate a subscriber served in macrocell M, say X_3, which can be moved to m_3. Then the channel of X_3 in M is vacated and can be allocated to R_2.

2.2. Channel sharing in the horizontal direction

By 'horizontal', we mean transferring calls between neighboring cells in the high tier. If the above vertical channel-sharing fails, a horizontal sharing will be take place. This is done by forcing a subscriber on M to take an early handoff as follows.

H1. Pick any macrocell M_i, $1 \le i \le v$, which is neighboring to M such that M_i has at least one free channel and there is a subscriber, say x, resident in the area that is covered by both M and M_i.
H2. If H1 succeeds, enforce subscriber x to take an early handoff to M_i to vacate a channel. If the channel request is made on the high tier, assign the vacated channel to the request directly; otherwise, overflow the request from the low tier to the high tier to use the vacated channel.

Fig. 2 shows an example. Users R_1 and R_2 arrive at cells m_1 and M_1, respectively, which have run out of channels. Users X_2 and X_3 are possible candidates to take early handoffs to M_2 and M_3, respectively.

Note that here we only consider horizontal sharing on the high tier. Although theoretically it is possible to take horizontal sharing among microcells, we tend to not do so because it is less practical considering the size of microcells. Also, the failure of our vertical channel-sharing implies that there are no free channels in microcells m_1, m_2,…,m_n covered by macrocell M. Thus the success possibility of doing so could be quite low.

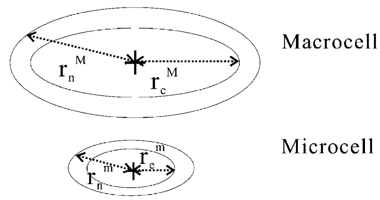

Fig. 3. Radii of the circles for a subscriber to take a normal handoff and an early handoff.

3. Performance analysis

3.1. Analysis model

In this section, we discuss some basic assumptions in our analysis. We assume that each macrocell covers n microcells. We assume that all cells in the same tier are statistically identical, and thus we can focus on the behavior of only one cell and its interaction with neighboring cells. Each macrocell and microcell is assumed to cover a circle. The radius of the circle for a subscriber to take a normal handoff on a macrocell is r_n^M, and that on a microcell is r_n^m. However, since there will be some overlapping between two macrocells/microcells, the radius of the circle for a subscriber to take an early handoff on a macrocell is r_e^M, and that on a microcell r_e^m. See Fig. 3 for an illustration.

The *cell dwell time* is the amount of time that a subscriber remains within a cell, which is assumed to be a random variable with a negative exponential probability density function with a certain mean. The cell dwell time can be derived by a fluid flow mobility model [14]. For fast and slow subscribers in a macrocell, the inverses of cell dwell time (or the cell cross-over rate) are

$$\eta_f^M = \frac{2V_f}{\pi r_n^M}, \qquad \eta_s^M = \frac{2V_s}{\pi r_n^M},$$

respectively, where V_f is the velocity of fast subscriber and V_s is the velocity of slow subscriber. Following Ref. [14], the handoff probabilities for fast and slow subscribers in a macrocell are, respectively

$$P_{fh}^M = \frac{\eta_f^M}{\mu + \eta_f^M}, \qquad P_{sh}^M = \frac{\eta_s^M}{\mu + \eta_s^M},$$

Table 2
Traffic parameters used in the analysis

Parameters	Macrocell		Microcell	
	Fast	Slow	Fast	Slow
New call traffic rate	λ_f^M			λ_s^m
Handoff traffic rate	λ_{fh}^M	λ_{sh}^M	λ_{fh}^m	λ_{sh}^m
Overflow traffic rate		λ_{sv}^M	λ_{fv}^m	
Vertical direction traffic rate	λ_{fvl}^M	λ_{svl}^M	λ_{fvl}^m	λ_{svl}^m
Horizontal direction traffic rate	λ_{fhl}^M	λ_{shl}^M		
Mean cell dwell time	$1/\eta_f^M$	$1/\eta_s^M$	$1/\eta_f^m$	$1/\eta_s^m$
Mean channel occupancy time	$1/\mu_f^M$	$1/\mu_s^M$	$1/\mu_f^m$	$1/\mu_s^m$
The aggregate traffic rate	λ_{tf}^M	λ_{ts}^M	λ_{tf}^m	λ_{ts}^m

where μ is the inverse of the mean unencumbered call duration time. The *unencumbered call duration* of a call is the amount of time that the call may remain in progress if it could continue to complete without being dropped, and it also follows a negative exponential distribution. According to Ref. [14], the mean channel occupancy time is the mean of minimum of unencumbered call duration and cell dwell time, which should be

$$\frac{1}{\mu_f^M} = \frac{1}{\mu + \eta_f^M}, \qquad \frac{1}{\mu_s^M} = \frac{1}{\mu + \eta_s^M}$$

for fast and slow subscribers, respectively.

Following a similar derivation, we can recalculate the above parameters for microcells:

$$\eta_s^m = \frac{2V_s}{\pi r_n^m}, \qquad \eta_f^m = \frac{2V_f}{\pi r_n^m}, \qquad P_{sh}^m = \frac{\eta_s^m}{\mu + \eta_s^m},$$

$$P_{fh}^m = \frac{\eta_f^m}{\mu + \eta_f^m}, \quad \frac{1}{\mu_s^m} = \frac{1}{\mu + \eta_s^m}, \quad \frac{1}{\mu_f^m} = \frac{1}{\mu + \eta_f^m}.$$

In the analysis, we will use traffic flows to evaluate the blocking probability by the Erlang's loss formula [15]. The traffic flows include new calls, handoff calls, and those incurred by vertical and vertical–horizontal channel-sharing. These traffic flows are all assumed to follow the Poisson process. The other parameters related to our analysis are summarized in Table 2.

3.2. Performance of using vertical channel-sharing

In this section, we analyze the performance of our vertical channel-sharing strategy. The goal is to derive the *call loss probabilities* P_{lf} and P_{ls} of new calls for fast and slow subscribers, respectively. This is the probability for a channel request being refused after our vertical channel-sharing. Fig. 4 shows how these probabilities are determined. So we have

$$P_{lf} = P_b^M P_b^m P_v, \qquad P_{ls} = P_b^m P_b^M P_v,$$

where P_v is the failure probability of vertical direction sharing

$$P_v = 1 - P_{sv}(1 - P_b^m), \tag{1}$$

where $1 - P_b^m$ is the probability that a microcell has at least one free channel and P_{sv} is the probability that there exists a subscriber, which is currently served by the macrocell and is covered by the microcell

$$P_{sv} = 1 - \left(\frac{n-1}{n}\right)^{c^M},$$

where $((n-1)/n)c^M$ represents the probability that all subscribers served in macrocell are not located in this particular microcell. Here the number of channels for macrocell and microcell are c^M and c^m, respectively. The P_b^M (resp., P_b^m) is the probability that a mobile subscriber sees no free channel in a macrocell (resp., microcell). We can use the

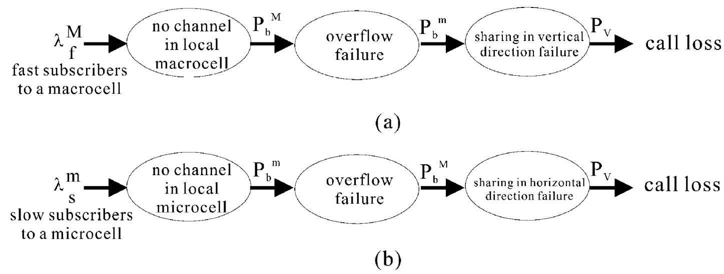

Fig. 4. Processes to choose a channel based on vertical channel-sharing when a request for a channel arrives: (a) high tier, and (b) low tier.

Erlang's loss formula to derive P_b^M and P_b^m :

$$P_b^M = \frac{\dfrac{\left(\dfrac{\lambda_{tf}^M}{\mu_f^M} + \dfrac{\lambda_{ts}^M}{\mu_s^M}\right)^{c^M}}{c^M!}}{\displaystyle\sum_{l=0}^{c^M} \dfrac{\left(\dfrac{\lambda_{tf}^M}{\mu_f^M} + \dfrac{\lambda_{ts}^M}{\mu_s^M}\right)^l}{l!}}, \tag{2}$$

$$P_b^m = \frac{\dfrac{\left(\dfrac{\lambda_{ts}^m}{\mu_s^m} + \dfrac{\lambda_{tf}^m}{\mu_f^m}\right)^{c^m}}{c^m!}}{\displaystyle\sum_{l=0}^{c^m} \dfrac{\left(\dfrac{\lambda_{ts}^m}{\mu_s^m} + \dfrac{\lambda_{tf}^m}{\mu_f^m}\right)^l}{l!}}. \tag{3}$$

Intuitively, the Erlang's loss formula is based on the M/M/m/m queuing system [16]. When a customer arrives, if all servers are occupied, the customer is lost. Let variables λ_{tf}^M, λ_{ts}^M, λ_{ts}^m, and λ_{tf}^m denote the arrival rates, and the μ_f^M, μ_s^M, μ_s^m, and μ_f^m denote the service rates for M/M/m/m queuing system (refer to Table 2 for their meanings). Here we regard $((\lambda_{tf}^M/\mu_f^M) + (\lambda_{ts}^M/\mu_s^M))$ and $((\lambda_{ts}^m/\mu_s^m) + (\lambda_{tf}^m/\mu_f^m))$ as the traffics contributed by subscribers on macrocell and microcell, respectively.

Next, we need to determine the four aggregate traffic rates λ_{tf}^M, λ_{ts}^M, λ_{ts}^m and λ_{tf}^m by following the analysis model in Ref. [12]. These traffics are composed of new calls, handoff calls, overflow calls, and channel-sharing calls are shown in Fig. 5. Variable λ_{tf}^M is the aggregate traffic rate incurred by new calls and handoff calls into a macrocell by fast subscribers:

$$\lambda_{tf}^M = \lambda_f^M + \lambda_{fh}^M,$$

where

$$\lambda_{fh}^M = \lambda_{tf}^M\left(1 - P_b^M\right)P_{fh}^M,$$

means the handoff rate is the aggregate traffic rate itself successfully stays in the macrocell $(\lambda_{tf}^M(1 - P_b^M))$ times the handoff probability (P_{fh}^M). Similarly, λ_{ts}^M is the aggregate traffic rate incurred by overflow calls and handoff calls into a macrocell by slow mobile subscribers:

$$\lambda_{ts}^M = \lambda_{sv}^M + \lambda_{sh}^M,$$

where

$$\lambda_{sv}^M = n\lambda_{ts}^m P_b^m,$$

means the overflow rate incurred by overflow from the n microcells covered by the macrocell. The second term λ_{sh}^M is the handoff calls into a macrocell by slow mobile subscribers, which equals the slow subscribers successfully staying on the high tier $(\lambda_{ts}^M(1 - P_b^M))$ times the handoff probability P_{sh}^M, that is

$$\lambda_{sh}^M = \left(\lambda_{ts}^M\right)\left(1 - P_b^M\right)P_{sh}^M.$$

Rate λ_{ts}^m is the summation of new calls, handoff calls, and calls caused by channel-sharing for slow subscribers:

$$\lambda_{ts}^m = \lambda_s^m + \lambda_{sh}^m + \lambda_{svl}^m,$$

where λ_{sh}^m is the handoff calls

$$\lambda_{sh}^m = \lambda_{ts}^m(1 - P_b^m)P_{sh}^m,$$

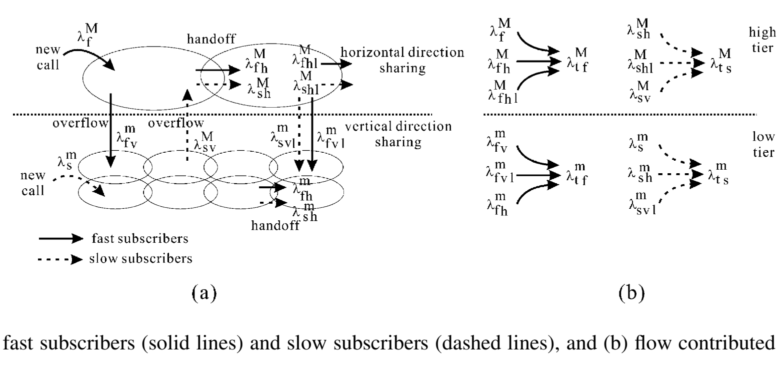

Fig. 5. (a) Traffic flows for fast subscribers (solid lines) and slow subscribers (dashed lines), and (b) flow contributed to the aggregate traffic rates.

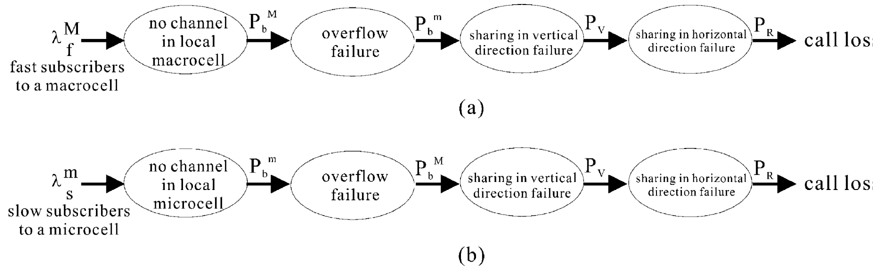

Fig. 6. Procedures to choose a channel based on vertical–horizontal channel-sharing when a request for a channel arrives: (a) fast subscriber, and (b) slow subscriber.

and $\lambda_{\rm svl}^{\rm m}$ is caused by our vertical channel-sharing strategy

$$\lambda_{\rm svl}^{\rm m} = \frac{1}{n}\left(\lambda_{\rm svl}^{\rm M} + \lambda_{\rm fvl}^{\rm M}\right)\frac{\lambda_{\rm ts}^{\rm M}}{\lambda_{\rm tf}^{\rm M} + \lambda_{\rm ts}^{\rm M}} P_{\rm sv}.$$

The summation $\lambda_{\rm svl}^{\rm M} + \lambda_{\rm fvl}^{\rm M}$ is the overall load caused by channel-sharing (including slow and fast subscribers) in the physical area covered by a macrocell (including one macrocell and n microcells), and times the probability that a subscriber in macrocell can be rearranged to a microcell ($P_{\rm sv}$), but only a fraction $1/n$ of the load will be injected to the microcell. Rate $\lambda_{\rm svl}^{\rm M}$, which counts for channel-sharing rates caused by slow subscribers, can be derived as

$$\lambda_{\rm svl}^{\rm M} = n\left(\lambda_{\rm s}^{\rm m} + \lambda_{\rm sh}^{\rm m}\right)P_{\rm b}^{\rm m}P_{\rm b}^{\rm M},$$

which equals the new call arrival rate and handoff rate of slow subscribers into the n microcells ($n(\lambda_{\rm s}^{\rm m} + \lambda_{\rm sh}^{\rm m})$), times the probability that they see no free channel in the local microcell ($P_{\rm b}^{\rm m}$), times the probability that they see no free channel in the macrocell ($P_{\rm b}^{\rm M}$). Rate $\lambda_{\rm fvl}^{\rm M}$, which counts for channel-sharing rates caused by fast subscribers, can be derived as

$$\lambda_{\rm fvl}^{\rm M} = \left(\lambda_{\rm f}^{\rm M} + \lambda_{\rm fh}^{\rm M}\right)P_{\rm b}^{\rm M}P_{\rm b}^{\rm m},$$

which equals the new call arrival rate and handoff rate into a macrocell ($\lambda_{\rm f}^{\rm M} + \lambda_{\rm fh}^{\rm M}$), times the probabilities that they see no free channel in the macrocell ($P_{\rm b}^{\rm M}$), and neither in the microcell ($P_{\rm b}^{\rm m}$). Finally, note that the last term ($\lambda_{\rm ts}^{\rm M}/(\lambda_{\rm tf}^{\rm M} + \lambda_{\rm ts}^{\rm M})$) is the ratio of channel-sharing flows by slow subscriber into microcells.

The last rate $\lambda_{\rm tf}^{\rm m}$ is the summation of handoff calls, overflow calls, and calls caused by channel-sharing for fast subscribers:

$$\lambda_{\rm tf}^{\rm m} = \lambda_{\rm fh}^{\rm m} + \lambda_{\rm fv}^{\rm m} + \lambda_{\rm fvl}^{\rm m},$$

where

$$\lambda_{\rm fh}^{\rm m} = \lambda_{\rm tf}^{\rm m}(1 - P_{\rm b}^{\rm m})P_{\rm fh}^{\rm m}, \qquad \lambda_{\rm fv}^{\rm m} = \frac{1}{n}\lambda_{\rm tf}^{\rm M}P_{\rm b}^{\rm M},$$

$$\lambda_{\rm fvl}^{\rm m} = \frac{1}{n}\left(\lambda_{\rm svl}^{\rm M} + \lambda_{\rm fvl}^{\rm M}\right)\frac{\lambda_{\rm tf}^{\rm M}}{\lambda_{\rm tf}^{\rm M} + \lambda_{\rm ts}^{\rm M}} P_{\rm sv}.$$

The rationale is similar to the previous rate. The handoff rate $\lambda_{\rm fh}^{\rm m}$ is the rate for fast subscribers successfully staying in microcell ($\lambda_{\rm tf}^{\rm m}(1 - P_{\rm b}^{\rm m})$), times the probability for them to take a handoff to neighboring microcells ($P_{\rm fh}^{\rm m}$). The overflow rate $\lambda_{\rm fv}^{\rm m}$ for fast mobile from macrocell to microcel is $(1/n)\lambda_{\rm tf}^{\rm M}P_{\rm b}^{\rm M}$. The $\lambda_{\rm fvl}^{\rm m}$ is caused by our vertical channel-sharing strategy, where the ratio $(\lambda_{\rm tf}^{\rm M}/(\lambda_{\rm tf}^{\rm M} + \lambda_{\rm ts}^{\rm M})$ is the ratio of channel-sharing flows by fast subscriber into microcells.

3.3. Performance of using vertical–horizontal channel-sharing

By using vertical–horizontal channel-sharing, a mobile subscriber, when seeing no free channel on its local cell, can take a vertical channel-sharing first. If this fails, a horizontal direction sharing can be taken. Again, our goal is to derive the *call loss probabilities* $P_{\rm lf}$ and $P_{\rm ls}$ of new calls for fast and slow subscribers, respectively. As shown in Fig. 6, we have

$$P_{\rm lf} = P_{\rm b}^{\rm M}P_{\rm b}^{\rm m}P_{\rm v}P_{\rm R}, \qquad P_{\rm ls} = P_{\rm b}^{\rm m}P_{\rm b}^{\rm M}P_{\rm v}P_{\rm R}.$$

Probability $P_{\rm v}$ is given in Eq. (1), where the $P_{\rm R}$ is the failure probability of horizontal direction sharing

$$P_{\rm R} = 1 - P_{\rm can}^{\rm M}\left(1 - P_{\rm b}^{\rm M}\right),$$

where $P_{\rm can}^{\rm M}$ is the probability for at least one subscriber staying in early handoff area

$$P_{\rm can}^{\rm M} = 1 - \left(\frac{\left(r_{\rm e}^{\rm M}\right)^2}{\left(r_{\rm n}^{\rm M}\right)^2}\right)^{c^{\rm M}}.$$

The $P_{\rm b}^{\rm M}$ and $P_{\rm b}^{\rm m}$ can be derived from Eqs. (2) and (3), respectively, but their values are different for different aggregate traffic rates. The horizontal direction sharing only affects the traffic flows on macrocell. So in microcells, the $\lambda_{\rm ts}^{\rm m}$ and $\lambda_{\rm tf}^{\rm m}$ are the same as that in vertical channel-sharing in Section 3.2, but their values are dependent on the $P_{\rm b}^{\rm M}$ and $P_{\rm b}^{\rm m}$ when horizontal direction sharing is used. In macrocells, the aggregate rate $\lambda_{\rm tf}^{\rm M}$ consists of new calls, handoff calls and horizontal direction sharing calls for fast subscriber:

$$\lambda_{\rm tf}^{\rm M} = \lambda_{\rm f}^{\rm M} + \lambda_{\rm fh}^{\rm M} + \lambda_{\rm fhl}^{\rm M},$$

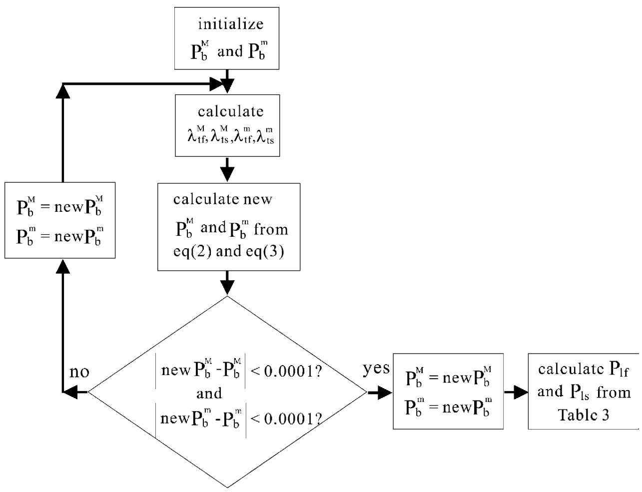

Fig. 7. Flowchart of our iterative method.

where $\lambda_{\mathrm{fhl}}^{\mathrm{M}}$ is caused by the horizontal direction sharing

$$\lambda_{\mathrm{fhl}}^{\mathrm{M}} = \left(\lambda_{\mathrm{f}}^{\mathrm{M}} + \lambda_{\mathrm{fh}}^{\mathrm{M}}\right) P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{v}} P_{\mathrm{can}}^{\mathrm{M}},$$

which equals the new call arrival rate and handoff rate into a macrocell ($\lambda_{\mathrm{f}}^{\mathrm{M}} + \lambda_{\mathrm{fh}}^{\mathrm{M}}$), times the probabilities that they see no free channel in the macrocell ($P_{\mathrm{b}}^{\mathrm{M}}$), and neither in the microcell ($P_{\mathrm{b}}^{\mathrm{m}}$), times the probability that they fail in vertical direction sharing (P_{v}), and times the probability for at least one subscriber staying in early handoff area ($P_{\mathrm{can}}^{\mathrm{M}}$). Similarly, ($\lambda_{\mathrm{ts}}^{\mathrm{M}}$) is the aggregate traffic rate incurred by overflow calls, handoff calls and horizontal direction sharing calls into a macrocell by slow mobile subscribers:

$$\lambda_{\mathrm{ts}}^{\mathrm{M}} = \lambda_{\mathrm{sv}}^{\mathrm{M}} + \lambda_{\mathrm{sh}}^{\mathrm{M}} + \lambda_{\mathrm{shl}}^{\mathrm{M}},$$

where ($\lambda_{\mathrm{shl}}^{\mathrm{M}}$) is caused by the horizontal direction sharing

$$\lambda_{\mathrm{shl}}^{\mathrm{M}} = n\left(\lambda_{\mathrm{s}}^{\mathrm{m}} + \lambda_{\mathrm{sh}}^{\mathrm{m}}\right) P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{v}} P_{\mathrm{can}}^{\mathrm{M}},$$

which equals the new call arrival rate and handoff rate of slow subscribers into the n microcells ($n(\lambda_{\mathrm{s}}^{\mathrm{m}} + \lambda_{\mathrm{sh}}^{\mathrm{m}})$), times the probabilities that they see no free channel in the local microcell ($P_{\mathrm{b}}^{\mathrm{m}}$), and neither in the macrocell ($P_{\mathrm{b}}^{\mathrm{M}}$), times the probability that they fail in vertical direction sharing (P_{v}), and times the probability for at least one subscriber staying in early handoff area ($P_{\mathrm{can}}^{\mathrm{M}}$).

Table 3
Comparison of call loss probabilities for fast and slow subscribers

	P_{lf}	P_{ls}
TB	$P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{b}}^{\mathrm{m}}$	$P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{b}}^{\mathrm{M}}$
CR	$P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{R}}$	$P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{r}} P_{\mathrm{b}}^{\mathrm{M}}$
VCS	$P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{v}}$	$P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{v}}$
VHCS	$P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{v}} P_{\mathrm{R}}$	$P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{v}} P_{\mathrm{r}}$

4. Performance comparisons

4.1. Numerical results

This section compares our strategy against the take-back (TB) strategy [12] and the channel rearrangement (CR) strategy [13]. Table 3 shows the call loss probabilities for fast and slow subscribers in these strategies. VCS is to apply our vertical channel-sharing only, and VHCS to apply our vertical–horizontal channel-sharing. The probabilities of TB are derived in Ref. [12], while those of CR are in Appendix A.

To see how these formulas are compared to each other, we plug-in the following parameters. The radius of macrocells is set to 400 m, while that of microcells 200 m. The average velocities are 5 and 30 km/h for slow and fast subscribers, respectively. The mean holding time of a call is 110 s. A macrocell covers n microcells. The call arrival rate is $p\lambda$ for each microcell, and $n(1-p)\lambda$ for each macrocell, where p is to tune the amount of fast subscribers in an area and n is to take care of size difference between macrocells and microcells. The numbers of channels owned by each macrocell and microcell are 29 and 7, respectively.

An iterative method is used to compute the call loss probabilities of the compared strategies. The flow chart of our iterative method is shown in Fig. 7. The results at various λ are in Fig. 8 for fast and slow subscribers. Here we use $n = 4$ and $p = 0.5$. For fast subscribers, the CR scheme only redirects traffic to neighboring macrocells when a macrocell is busy. The traffic load is not released effectively, so it performs the worst, as shown in the figure. The TB scheme overflows a call to the overlaid microcell with take-back strategy at cell boundaries and thus performs

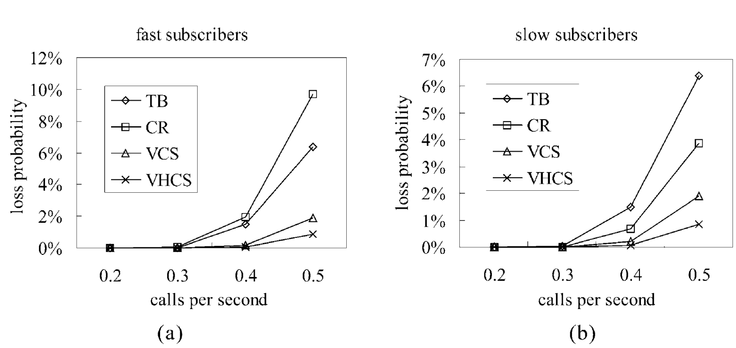

Fig. 8. Comparison based on numerical analysis on call loss probability for: (a) fast subscribers and (b) slow subscribers.

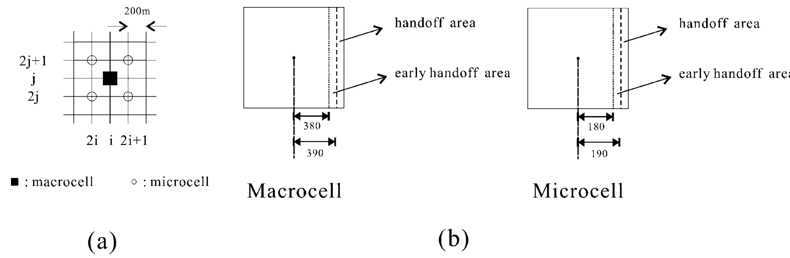

Fig. 9. Simulation environment: (a) cell deployment and (b) handoff area and early handoff area.

better. Our VCS scheme not only overflows a call to the overlaid microcell, but also pushes other calls on the macrocell to its overlaid microcell, if necessary. Intuitively, we use multiple microcells to 'absort' to load on the macrocell. So it gives much lower call loss probability. Our VHCS scheme performs even better than VCS if horizontal direction sharing is taken.

For slow subscribers, the trend is similar to VCS and VHCS, but CR is better than TB. This is because CR takes a channel rearrangement strategy following an overow scheme, which gives more redirecting choices than TB between two tiers.

4.2. Simulation results

To verify our performance analysis, we have also developed a simulator. The simulation environment is set up similar to our analysis model. An area with 9 × 9 macrocells and 18 × 18 microcells are simulated by wrapping around at the edges to avoid edge effects. Each macrocell covers four microcells as shown in Fig. 9(a). For simplicity, each cell is of a square shape, with macrocells being 800 m × 800 m and microcells being 400 m × 400 m. Mobile subscribers roam in only east, west, north, and south directions. The area to take handoff and early handoff are shown in Fig. 9(b).

To compare call loss probability, in our simulations, we follow the CR strategy [13] that subscribers are never taken back to their preferred tier when they have overflowed to another tier. The VCS and VHCS also follow such rules. On the contrary, in the TB strategy, subscribers only stay on the overflowed tier if the take-back fails. The simulation results on call loss probability are in Fig. 10. The results are quite close to our numerical results based on analysis, which shows the correctness of our analysis. Note that each simulation result was obtained from the average of 50 simulation runs, where in each run a total of 60,000 call requests were generated. The confidence level of our simulations was quite high. For example, in Table 4, we show the variance and confidence interval at 95% for fast subscribers when the traffic rate is 0.5 calls/s.

Another thing we have not observed is the *call dropping probability*, which is defined to be the probability that a call will be forced to terminate because of no available channels at the events of handoffs. This is very undesirable from the users' point of view. In the call dropping simulation, all the TB, CR, VCS, and VHCS adopt the assumption that the target tier for handoff is always the preferred tier. The outcomes of the call dropping probability shown in Fig. 11 are like the trend of Fig. 10. The worst performance for fast and slow subscriber is the CR and TB, respectively. The VCS reveals a good performance for fast and slow subscriber. The best performance is the VHCS in our simulation. The gap between CR/TB and VCS/VHCS is reduced for fast subscriber, but the gap is enlarged between TB/CR and VCS/VHCS for slow subscriber.

Table 4
Statistical values of loss probabilities for fast subscribers with traffic rate = 0.5 calls/s

Strategies	Means (%)	Variance (%)	Confidence interval (%)
TB	7.154179	0.000421	(7.097331, 7.211027)
CR	9.281282	0.000808	(9.202483, 9.360081)
VCS	2.574234	0.000161	(2.539081, 2.609387)
VHCS	1.684051	0.000168	(1.648173, 1.719929)

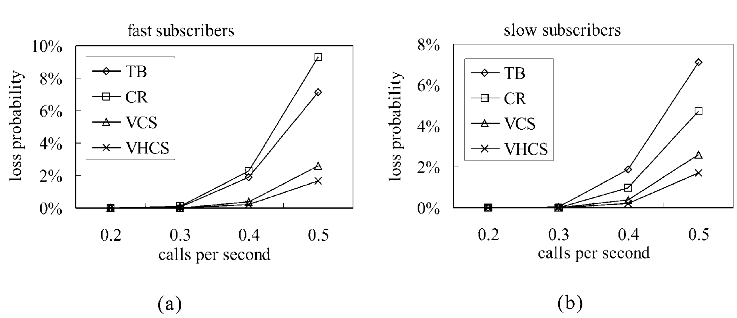

Fig. 10. Comparison based on simulation on call loss probability for: (a) fast subscribers and (b) slow subscribers.

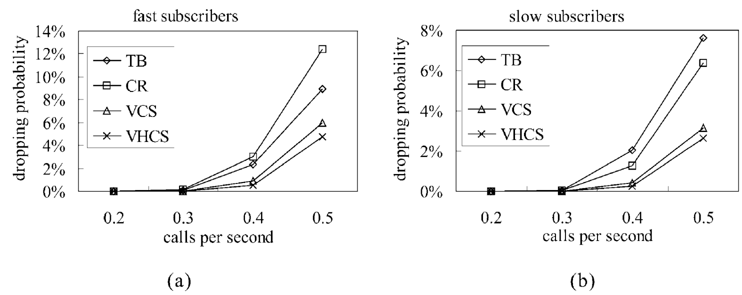

Fig. 11. Comparison based on simulation on call dropping probability for: (a) fast subscribers and (b) slow subscribers.

The lower call dropping probability of our schemes is contributed by a higher handoff success probability. To understand the distribution of different ways to redirect a call to different cells/tiers in events of handoff, we also observe how a handoff is handled through our simulations. The result is shown in Fig. 12. For TB, CR, VCS, and VHCS, we count the number of successful and unsuccessful handoffs. For successful handoffs, it is further divided into four cases: normal, overflow, vertical direction, and horizontal direction. As can be seen, the total numbers of successful handoffs of VCS and VHCS significantly outperform those of TB and CR. This justifies what we concluded in Table 1 that there are more ways to redirect a call in our channel-sharing strategies. Comparing vertical direction and horizontal direction handoffs, vertical direction handoffs can absorb a lot of handoffs. So VCS is quite effective, and yet easy to implement.

5. Conclusions

In this paper, we have proposed two channel-sharing strategies to improve the performance of a two-tier cellular system. The main idea is to share, and thus fully utilize, the channels owned by overlapping macrocells and microcells. Performance analyses based on fluid flow model and simulations are presented. Significant reduction in call loss probability and call dropping probability can be obtained over existing schemes by simply using our vertical channel-sharing strategy. The vertical–horizontal channel-sharing combining the vertical channel-sharing and horizontal direction sharing can even slightly increase the number of calls being accepted.

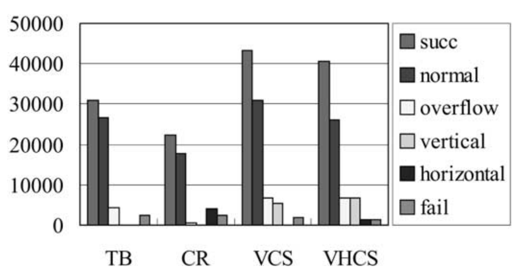

Fig. 12. Handoff distributions TB, CR, VCS, and VHCS. The total numbers of successful and unsuccessful handoffs are indicated by 'succ' and 'fail', respectively. Successful handoffs are further classified into normal, overflow, vertical direction, and horizontal direction, based on different strategies.

Acknowledgements

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Appendix A. Performance of channel rearrangement

In this appendix, we analyze the performance of channel rearrangement strategy [13]. The goal is to derive the *call loss probabilities* P_{lf} and P_{ls} of new calls for fast and slow subscribers, respectively.

This is the probability for a channel request being refused after the channel rearrangement. Fig. A1 shows how these probabilities are determined. So we have

$$P_{\mathrm{lf}} = P_{\mathrm{b}}^{\mathrm{M}} P_{\mathrm{R}}, \qquad P_{\mathrm{ls}} = P_{\mathrm{b}}^{\mathrm{m}} P_{\mathrm{r}} P_{\mathrm{b}}^{\mathrm{M}},$$

where P_{R} and P_{r} is the failure probability of channel rearrangement in macrocell and microcell, respectively

$$P_{\mathrm{R}} = 1 - P_{\mathrm{can}}^{\mathrm{M}}\left(1 - P_{\mathrm{b}}^{\mathrm{M}}\right), \qquad P_{\mathrm{r}} = 1 - P_{\mathrm{can}}^{\mathrm{m}}\left(1 - P_{\mathrm{b}}^{\mathrm{m}}\right),$$

where $P_{\mathrm{can}}^{\mathrm{M}}$ (resp., $P_{\mathrm{can}}^{\mathrm{m}}$) is the probability for at least one subscriber staying in early handoff area in a macrocell (resp., microcell)

$$P_{\mathrm{can}}^{\mathrm{M}} = 1 - \left(\frac{\left(r_{\mathrm{e}}^{\mathrm{M}}\right)^2}{\left(r_{\mathrm{n}}^{\mathrm{M}}\right)^2}\right)^{c^{\mathrm{M}}}, \qquad P_{\mathrm{can}}^{\mathrm{m}} = 1 - \left(\frac{\left(r_{\mathrm{e}}^{\mathrm{m}}\right)^2}{\left(r_{\mathrm{n}}^{\mathrm{m}}\right)^2}\right)^{c^{\mathrm{m}}}.$$

The $P_{\mathrm{b}}^{\mathrm{M}}$ and $P_{\mathrm{b}}^{\mathrm{m}}$ can also be derived from Eqs. (2) and (3), respectively, but their value are different for different aggregate traffic rate described as follows. In macrocell, the aggregate rate $\lambda_{\mathrm{tf}}^{\mathrm{M}}$ consists of new calls, handoff calls and channel rearrangement calls for fast subscriber:

$$\lambda_{\mathrm{tf}}^{\mathrm{M}} = \lambda_{\mathrm{f}}^{\mathrm{M}} + \lambda_{\mathrm{fh}}^{\mathrm{M}} + \lambda_{\mathrm{fcr}}^{\mathrm{M}},$$

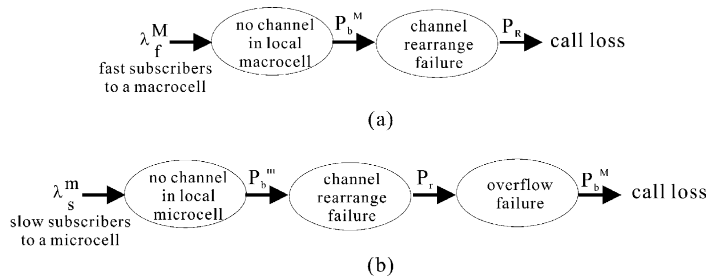

Fig. A1. Procedures to choose a channel based on channel rearrangement when a request for a channel arrives: (a) fast subscriber, and (b) slow subscriber.

where $\lambda_{\rm fcr}^{\rm M}$ is the channel rearrangement rate for fast subscribers in macrocell

$$\lambda_{\rm fcr}^{\rm M} = \left(\lambda_{\rm f}^{\rm M} + \lambda_{\rm fh}^{\rm M}\right)P_{\rm b}^{\rm M}P_{\rm can}^{\rm M},$$

which equals the new call arrival rate and handoff rate into a macrocell, times the probability that they see no free channel in the macrocell ($P_{\rm b}^{\rm M}$), and times the probability for at least one subscriber staying in early handoff area in a macrocell ($P_{\rm can}^{\rm M}$).

The $\lambda_{\rm ts}^{\rm M}$ consists of overflow calls and handoff calls for slow subscriber in macrocell:

$$\lambda_{\rm ts}^{\rm M} = \lambda_{\rm sv}^{\rm M} + \lambda_{\rm sh}^{\rm M},$$

where the rate of overflow calls from n microcells to a macrocell is

$$\lambda_{\rm sv}^{\rm M} = n\lambda_{\rm ts}^{\rm m}P_{\rm b}^{\rm m}P_{\rm r}.$$

In microcell, the $\lambda_{\rm ts}^{\rm m}$ consists of new call, handoff calls and channel rearrangement calls for slow subscriber:

$$\lambda_{\rm ts}^{\rm m} = \lambda_{\rm s}^{\rm m} + \lambda_{\rm sh}^{\rm m} + \lambda_{\rm scr}^{\rm m},$$

where $\lambda_{\rm scr}^{\rm m}$ is the channel rearrangement rate for slow subscribers in microcell

$$\lambda_{\rm scr}^{\rm m} = (\lambda_{\rm s}^{\rm m} + \lambda_{\rm sh}^{\rm m})P_{\rm b}^{\rm m}P_{\rm can}^{\rm m},$$

which equals the new call arrival rate and handoff rate into a microcell, times the probability that they see no free channel in the microcell ($P_{\rm b}^{\rm m}$), and times the probability for at least one subscriber staying in early handoff area in a microcell ($P_{\rm can}^{\rm m}$). The rate $\lambda_{\rm tf}^{\rm m}$ is equal to zero, because there are no any overflow calls from macrocell.

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