

# Teletraffic Modeling and Analysis of Flexible Hierarchical Cellular Networks with Speed-Sensitive Handoff Strategy

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**Abstract**—Hierarchical cellular networks with subscribers of varying mobility are considered. Microcells are used to address the high-intensity traffic of mainly slow mobility areas, and macrocells are overlaid over the microcells to cater mainly to high-mobility lower density traffic. The two tiers of microcells and macrocells provide a secondary resource for new traffic as well as handoffs for mobile subscribers of different mobility classes. Furthermore, resources in alternate layers are monitored to assign the appropriate resource types when they become available. We develop an analytical model to evaluate the performance of such systems, and quantify the gain obtained by providing overflow to alternate resources as well as the advantages in resource reassignment according to the speed classification.

## I. INTRODUCTION

THE increasing demand for cellular communications access and the evolution of wireless networks toward personal communication systems require a substantial increase of traffic capacity and full coverage of the service area. Among the different possible approaches to meet the traffic demand, attention is being paid to the microcellular systems with an overlay structure. The hierarchical structure of cells serves two purposes. First, the cells of small and large radius provide a more economically efficient system for higher and lower traffic densities, respectively. Second, subscribers of lower and higher mobility can efficiently be provided service in the small cells and umbrella cells, respectively.

In general, small cells will give rise to a higher number of cell boundary crossings for high-mobility users, and the resulting number of handoffs of calls in progress may cause an excessive processing load in the network. Furthermore, the time required to perform handoffs may be critical for high-mobility subscribers in microcells due to a specific propagation environment (e.g., street corner effect) [1]. Therefore, particular attention should be paid to the design of handoff algorithms for a hierarchical system to balance the loading with the desired quality of service.

In a hierarchical system, cells of different sizes in a multitiered structure provide multiple service coverage of subscribers of various mobility classes. Speed-sensitive cell selection, cell reselection, and handoff procedures are defined for a

flexible hierarchical system to direct the mobile subscribers to the appropriate cell layer according to their speeds. The radio link control procedures have to support the operation of the mobile subscriber in this multitier cell environment.

Traffic handling in hierarchical cell architectures comprises several steps.

- Cell selection and reselection of mobile stations<sup>1</sup> for camping on a cell in idle mode may be speed sensitive or insensitive.
- A speed-sensitive handoff algorithm uses, in addition to measurements of received signal levels of the serving and neighboring cells, the estimated mean speed of the mobile station to decide on the target cell layer where the call has to be handed off. The local mean speed estimate can be based on the recent, and possibly on past, microcell dwell times, on serving cell session time, and or combinations of these time periods.
- Overflow strategies are considered to increase the system capacity for specific mobility classes under a predefined grade of service.

Systems employing multitiered cells have been considered in a number of publications. Several methods for handling new calls and handoff traffic of the defined mobile subscriber speed classes are proposed, and performance measures such as the probability of new call blocking, probability of forced termination, and traffic capacity have been determined. In the case of a speed-insensitive selection mechanism, call originations are assigned to a default cell layer which is, in most cases, the lowest (microcell) layer [2], [3]. If a speed-sensitive selection mechanism is used, arriving calls can be directed to the specific cell layer dependent on the speed class of the mobile station. Examples are given in [4]–[6]. Speed estimation can be based on the recent cell dwell time or past dwell times can be taken into account. In [6], the probability of erroneous assignment of a mobile station to a microcell or macrocell is shown for various approaches.

For the speed-sensitive handoff algorithm, different approaches are proposed in [2], [3], and [5]–[7]. In [8] and [10], new call and handoff attempts are overflowed from the speed-dependent preferred cell layer to an upper cell layer if they cannot be served by an idle traffic channel in the preferred layer. In addition, handoff calls can be given priority

<sup>1</sup>For brevity, we use the terms “mobile stations” and “mobile subscribers” interchangeably.

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access in specific cell layers by applying the concept of guard channels (e.g., [8] and extensions in [9]). In [3], overflow from the microcell to the macrocell layer is restricted to handoff attempts. In [11], mobile stations traveling in the microcellular cluster may borrow traffic channels from a pool of reserved handoff channels provided by the overlaying macrocell.

Other papers have also considered similar mechanisms. The overflow strategy which is commonly applied is constrained to one direction from small cells in lower layers to larger cells in higher layers. In [12], the mobile station reassigns its connection to the microcell in which it is traveling as soon as a channel becomes available in the cell. However, to the authors' knowledge, a flexible both-way overflow mechanism with possible take-back of overflow traffic into the preferred cell layer has not been considered in these studies.

In this paper, a two-layer cell architecture is considered. The lower cell layer employs microcells providing coverage primarily for slow-moving mobile subscribers, while the upper cell layer consist of macrocells serving primarily fast-moving mobile subscribers. A homogeneous network of cells in each layer is assumed, where both layers provide continuous radio coverage. In the following, we describe the cell selection procedures for mobile subscribers in "idle" and "connected" modes.

The mobile subscribers, while in the idle mode, have the capability to select cells in a prioritized manner depending on their speed. Slow mobile stations will camp on microcells, while fast mobile stations will camp on macrocells. An example for a speed-sensitive cell (re)selection algorithm used in an operating cellular system is described in [4].

As for the idle mode, a speed-sensitive handoff procedure is used in the "connected" mode. The algorithm enables the network to clear on the handoff target cell depending on the user's mobility. Various criteria can be used to estimate the absolute speed of the mobile station, e.g., the time over which the mobile station remains within the serving area of a cell. In [7], possible candidate algorithms for an operating cellular system are described. Reference [13] investigates the handoff failure probability using simulations based on measured propagation profiles in a typical metropolitan environment.

In addition to the speed-sensitive handoff decision, the handoff procedure provides overflow for new call and handoff attempts to the upper and lower cell layer, respectively, if target cells on the same layer have no traffic channels available. Since the handoff algorithm is controlled by the network, overflow to the lower layer can be restricted to cells which are capable of handling fast mobile stations. Furthermore, the handoff procedure provides a *take-back* capability for new and handoff calls which have been accepted to the system as overflow. These calls are taken back to a cell of the appropriate layer as soon as traffic channels become available. This capability has the effect that the number of mobile stations with differing speed is minimized in the considered cell layer.

The handoff strategy assumed in the present contribution, on one hand, provides a speed-sensitive separation of mobile station to the appropriate cell layer, and on the other hand, offers maximum flexibility with respect to overflow traffic.

Our intent here is to gain insight into the behavior of the flexible two-tiered hierarchical system. We will take into consideration reasonable practical assumptions to use approximate methods and refer to well-established principles in teletraffic theory to achieve this objective. We contrast the behavior of the system under consideration with those with less flexibility through numerical examples. Although in the two-tier model we consider microcell and overlaid cells, we note that there are other scenarios to which the analysis presented here may be applicable.

## II. SYSTEM DESCRIPTION

A large geographical area covered by contiguous microcells as depicted in Fig. 1 is considered. These microcells constitute the lower layer of the two-layer hierarchy. Every  $N$  microcells are overlaid by a large macrocell. The overlaying macrocells form the upper cell layer. Each macrocell is allocated  $c_0$  traffic channels, and the number of channels allocated to microcell  $i$  is  $c_i$ ,  $i = 1, 2, \dots, N$ . All channels are shared among new calls and handoff calls, i.e., no prioritization of handoff calls by means of reserved guard channels is used. The consideration is made since the handoff prioritization does not add any additional insight. However, analysis developed in this paper can readily be extended to include the guard channels.

In our system, a large number of mobile stations is traversing randomly the coverage area of the cell. However, we distinguish two classes of fast and slow mobile stations. We further assume that a mobile station does not change its speed class (during a call).

The operation of the system can be described as follows (see Fig. 2).

- A new call generated by a slow mobile station is first directed to the camped-on microcell. If the number of traffic channels in use in the microcell  $i$  is equal to  $c_i$ , this new call may be overflowed to the overlaying macrocell. The overflowed new call will be accepted by the macrocell if the number of traffic channels occupied in the macrocell is less than  $c_0$ ; otherwise, the call will be lost.
- A new call generated by a fast mobile station is first directed to the camped-on macrocell. If the number of traffic channels in use in the macrocell is equal to  $c_0$ , this new call may be overflowed to that overlaid microcell which provides radio coverage to the mobile station. This new call will be served by the microcell if the number of traffic channels occupied in this microcell  $i$  is less than  $c_i$ ; otherwise, it will be lost.
- A handoff request of a slow mobile station is first directed to the target microcell independent of whether the current serving cell is a neighboring microcell or an overlaying macrocell. If all traffic channels in the target microcell are busy, the handoff request may be overflowed to the overlaying macrocell. The overflowed handoff request will be served by the macrocell if there is any idle traffic channel; otherwise, the handoff request will fail and the call will be forced to terminate (dropped).

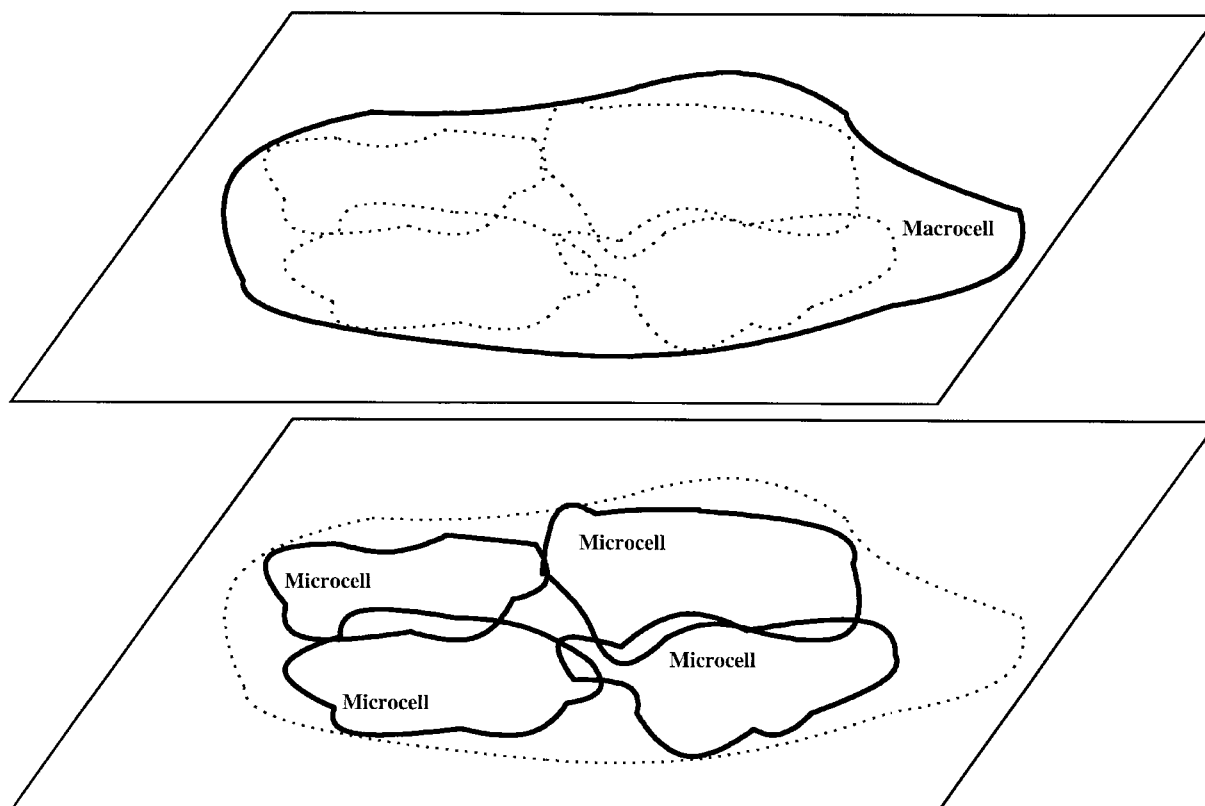


Fig. 1. Macrocell and microcell hierarchy structure.

- A handoff request of a fast mobile station is first directed to the target macrocell independent of whether the current serving cell is a neighboring macrocell or a neighboring microcell. If all traffic channels in the target macrocell are busy, the handoff request may be overflowed to the neighboring microcell, which will provide radio coverage for the mobile station. The overflowed handoff request will be served by the microcell if there is any idle traffic channel; otherwise, the handoff request will fail and the call will be forced to terminate (dropped).
- While a slow mobile station is roaming within a macrocell, it monitors continuously the microcell it is traversing. If this slow mobile station is engaged in a new or handoff call that has been successfully overflowed to the macrocell, a take-back request is directed to the entered target microcell at each border crossing of a microcell. This take-back request will be accommodated by the target microcell if there is any idle traffic channel in the microcell. If all traffic channels in the target microcell are busy, the slow mobile station will continue to be served in the macrocell. This algorithm makes the simplifying assumption that the take-back process, normally expected to take place as soon as a channel in the microcell becomes available, is delayed until microcell border crossings.
- If a fast mobile station is engaged in a new or handoff call that has been successfully overflowed to a microcell, a take-back request is directed to the overlaying macrocell at the border crossing of the microcell. This take-back request will be accommodated by the target macrocell if there is any idle traffic channel in the macrocell. If all

traffic channels in the target macrocell are busy, the fast mobile station initiates a handoff request to a neighboring microcell, which will provide radio coverage. This algorithm takes into account the practical considerations on the use of handoff and delays the take-back process until the border-crossing epochs (as opposed to whenever a channel in the microcell becomes available). This reasonable simplifying assumption renders a tractable solution.

In our system, all microcells of the lower cell layer are treated equivalently to simplify the understanding of the overflow and take-back mechanisms. However, the presented methods can be extended to cases where it is useful to discriminate between microcells which share a portion of their border with the border of the overlaying macrocell and those microcells which are situated in the core of the macrocell.

### III. MODEL DESCRIPTION

In the considered homogeneous case, all cells of the same hierarchical level are statistically identical. In the equilibrium state, the overall system can be analyzed by focusing on only one given cell in each level. Therefore, we consider the statistical behavior of such cells under the condition that their neighboring cells will exhibit similar statistical behavior independently.

In this section, we define our system parameters and proceed to describe our model. We consider two populations of mobile stations, which are classified as low- and high-mobility mobile stations. The optimum spectral efficiency through frequency

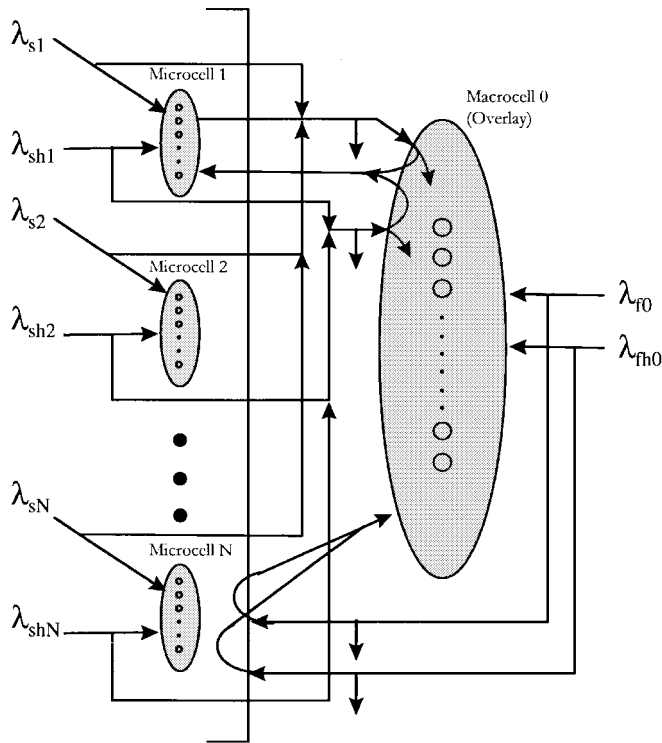


Fig. 2. Flow of new and handoff traffic, their overflow, and take-back traffic in hierarchical cell.

reuse can be achieved if the traffic of low-mobility mobile stations is carried by microcell channels and the traffic of high-mobility mobile stations is carried by macrocell channels, respectively. The radio link control procedures described in Section II support the allocation of mobile stations to the different cell layers dependent on their mobility class.

The total arriving traffic to the area  $\Omega$  is denoted by  $\lambda$ . The area under consideration has one overlaying macrocell and  $N$  microcells  $i = 1, 2, \dots, N$  (see Fig. 2). For simplicity, we assume<sup>2</sup> that the microcells are all identical circles with radius  $r_1$  and the macrocells are circles with radius  $r_0$ . New traffic solely generated by fast mobile stations is according to a Poisson process with parameter  $\lambda_{f0}$ . New traffic solely generated by slow mobile stations in microcell  $i$ ,  $i = 1, 2, \dots, N$  is according to a Poisson process with parameter  $\lambda_{si}$  (see Fig. 2). The average speed of the slow and fast mobile subscribers is considered to be  $V_s$  and  $V_f$ , respectively.

The calls arriving from fast or mobile subscribers have an encumbered call duration according to a negative exponential distribution with parameter  $\mu$ . The unencumbered call duration is the amount of time that the call would remain in progress if it could continue to completion without forced termination (by handoff failure).

We assume that the cell dwell time, that is, the time spent by a mobile station in a cell independent of being engaged in a call, is a random variable approximated by a negative exponential probability density function (pdf) [14], [15]. For macrocells, the parameters of the exponential pdf for fast and slow mobile stations are denoted by  $\eta_0$  and  $\eta'_0$ , respectively.

<sup>2</sup>With this assumption, the subscripts 0 and 1 refer to the macrocell and microcell, respectively.

Similarly, for microcells, we designate the parameters by  $\eta_1$  and  $\eta'_1$  for slow and fast mobile stations, respectively.

With the two assumptions above, the channel occupancy times, that is, the time spent in a cell by a mobile station being involved in a call, will follow negative exponential distributions.

For a macrocell, we denote the handoff rate of calls from fast and slow mobile stations by  $P_{h0}$  and  $P'_{h0}$ , respectively, and for a microcell for slow and fast mobile stations by  $P_{h1}$  and  $P'_{h1}$ , respectively.

The handoff traffic from slow and fast mobile stations in microcells and macrocells is denoted as follows.

- $\lambda_{fho}$  Rate of fast mobile station handoff traffic in a macrocell.
- $\lambda'_{sh0}$  Rate of slow mobile station handoff traffic in a macrocell.
- $\lambda_{sh1}$  Rate of slow mobile station handoff traffic in a microcell.
- $\lambda'_{fh1}$  Rate of fast mobile station handoff traffic in a microcell.

We define the take-back probability from a macrocell (moving slow mobile stations back to microcells) and microcell (moving fast mobile stations back to macrocells) by  $\zeta_s$  and  $\zeta_f$ , respectively.

We denote the take-back traffic rate to macrocell and microcell by  $\lambda_{fb0}$  and  $\lambda_{sb1}$ , respectively.

#### IV. PERFORMANCE MEASURES AND ANALYSIS

In this section, we will present analytical results for our system. As stated, our objective is to focus on simple tractable analytical results to obtain insight. To develop a quantitative analysis for this quite complex flexible hierarchical system, we make the following assumptions.

- 1) Use of fluid flow mobility model and derivation of slow and fast mobile stations' cell dwell times in a microcell and macrocell.
- 2) Treating the overflow traffic as Poisson. Our simulation results indicate that the analytical results using this assumption will be approximative and valid for realistic cases of interest. The simulation results also indicate that the obtained analytical results provide a useful comparison of performance for various cases discussed in this paper.
- 3) The take-back process is delayed until the cell boundary crossing (or virtual boundary crossings, i.e., at the end of the microcell dwell time of a slow mobile station). In other words, when a channel becomes available in the macrocell, the process of moving the fast mobile station from a channel in the microcell to the channel in the macrocell is delayed until it crosses the microcell boundary and requests a handoff. Similarly, when a channel becomes available in the microcell, the process of moving the slow mobile station from a channel in the macrocell to a channel in the microcell is delayed until it crosses the microcell boundary (which we refer to as the virtual boundary). In practice, this may also not be

unreasonable as it will result in less undesirable handoff executions.

In order to obtain the mean channel occupancy times, the mean cell dwell times, or their inverse, the cell boundary-crossing parameters need to be calculated. Using a fluid flow mobility model, the cell boundary crossings can be derived as follows for a macrocell (see, for example, [14] and [16]):

$$\begin{aligned}\eta_0 &= \frac{2V_f}{\pi r_0} \\ \eta'_0 &= \frac{2V_s}{\pi r_0} = \eta_0 \frac{V_s}{V_f}.\end{aligned}\quad (1)$$

The handoff probability of calls of slow and fast mobile stations in a macrocell is calculated from [14]

$$\begin{aligned}P_{h0} &= \frac{\eta_0}{\mu + \eta_0} \\ P'_{h0} &= \frac{\eta'_0}{\mu + \eta'_0}\end{aligned}\quad (2)$$

and the session duration of slow and fast mobile stations in macrocell is given by

$$\begin{aligned}\frac{1}{\mu_0} &= \frac{1}{\mu + \eta_0} \\ \frac{1}{\mu'_0} &= \frac{1}{\mu + \eta'_0}.\end{aligned}\quad (3)$$

Similarly, in a microcell, we can write

$$\begin{aligned}\eta_1 &= \frac{2V_s}{\pi r_1} \\ \eta'_1 &= \frac{2V_f}{\pi r_1} = \eta_1 \frac{V_f}{V_s}.\end{aligned}\quad (4)$$

The handoff probability of calls for slow and fast mobile stations in a microcell is calculated as

$$\begin{aligned}P_{h1} &= \frac{\eta_1}{\mu + \eta_1} \\ P'_{h1} &= \frac{\eta'_1}{\mu + \eta'_1}.\end{aligned}\quad (5)$$

The session duration of slow and fast mobile stations in a microcell is given by

$$\begin{aligned}\frac{1}{\mu_1} &= \frac{1}{\mu + \eta_1} \\ \frac{1}{\mu'_1} &= \frac{1}{\mu + \eta'_1}.\end{aligned}\quad (6)$$

We need to obtain the take-back probability from a macrocell (moving slow mobile stations back to microcells) and a microcell (moving fast mobile stations back to macrocells). Using our simplifying assumption 3), we can obtain estimates for these probabilities as follows:

$$\begin{aligned}\zeta_s &= P_{h1} \\ \zeta_f &= 0.\end{aligned}\quad (7)$$

Note that the last relation is due to our treatment of fast mobile station calls in microcell where the handoff processes will take the mobile stations back to the macrocell.

Now, we proceed to derive the performance measures for the fast and slow mobile stations. We have the following processes.

- 1) The traffic rate to microcells includes the rate of new arrivals  $\lambda_{s1}(1 - P_{b1})$  and the rate of accepted handoff traffic  $\lambda_{sh1}(1 - P_{b1})$  for slow mobile stations and overflow of new and accepted handoff calls of fast mobile stations from a macrocell, that is,  $\lambda_{f0}P_{b0}(1 - P_{b1})$  and  $\lambda_{fh0}P_{b0}(1 - P_{b1})$ .
- 2) The aggregate traffic rate into a microcell due to slow mobile stations is as follows:

$$\lambda_{t1} = \lambda_{s1} + \lambda_{sh1} + \lambda_{sb1} \quad (8)$$

where the take-back traffic rate component is given as

$$\lambda_{sb1} = (\lambda_{s1} + \lambda_{sh1} + \lambda_{sb1})P_{b1}(1 - P_{b0})\zeta_s. \quad (9)$$

- 3) The aggregate traffic rate into a microcell due to fast mobile stations is given as

$$\lambda'_{t1} = \frac{1}{N} (\lambda_{f0} + \lambda_{fh0} + \lambda_{fb0})P_{b0} + \lambda'_{fh1}, \quad (10)$$

- 4) The generation rate of slow mobile stations' handoff traffic in a microcell is as follows:

$$\lambda_{sh1} = P_{h1}[\lambda_{s1} + \lambda_{sh1} + \lambda_{sb1}](1 - P_{b1}). \quad (11)$$

- 5) The generation rate of fast mobile stations' handoff traffic in a microcell is as follows:

$$\begin{aligned}\lambda'_{fh1} &= P'_{h1} \left\{ \frac{1}{N} [\lambda_{f0} + \lambda_{fh0} + \lambda_{fb0}]P_{b0}(1 - P_{b1}) \right. \\ &\quad \left. + \lambda'_{fh1}(1 - P_{b1}) \right\}.\end{aligned}\quad (12)$$

- 6) The traffic rate to a macrocell includes the rate of new arrivals  $\lambda_{f0}(1 - P_{b0})$  and the rate of accepted handoff traffic  $\lambda_{fh0}(1 - P_{b0})$  from fast mobile stations and the overflow rate of new and accepted handoff calls of slow mobile stations from the microcell, that is,  $\sum_{i=1}^N \lambda_{si}P_{b1}(1 - P_{b0})$  and  $\sum_{i=1}^N \lambda_{shi}P_{b1}(1 - P_{b0})$ .
- 7) The aggregate traffic rate due to fast mobile stations into a macrocell is as follows:

$$\lambda_{t0} = \lambda_{f0} + \lambda_{fh0} + \lambda_{fb0} \quad (13)$$

where the take-back traffic rate component is given as

$$\lambda_{fb0} = (\lambda_{f0} + \lambda_{fh0} + \lambda_{fb0})P_{b0}(1 - P_{b1})\zeta_f. \quad (14)$$

Note that due to our assumption above and 7), the take-back traffic has appeared in the form of a hand-off, and therefore no additional contribution will be present.

- 8) The aggregate traffic rate due to slow mobile stations into a macrocell is given as

$$\lambda'_{t0} = N(\lambda_{s1} + \lambda_{sh1} + \lambda_{sb1})P_{b1} + \lambda'_{sh0}. \quad (15)$$

- 9) The generation rate of fast mobile stations' handoff traffic in a macrocell is as follows:

$$\lambda_{fh0} = P_{h0}[\lambda_{f0} + \lambda_{fh0} + \lambda_{fb0}](1 - P_{b0}). \quad (16)$$

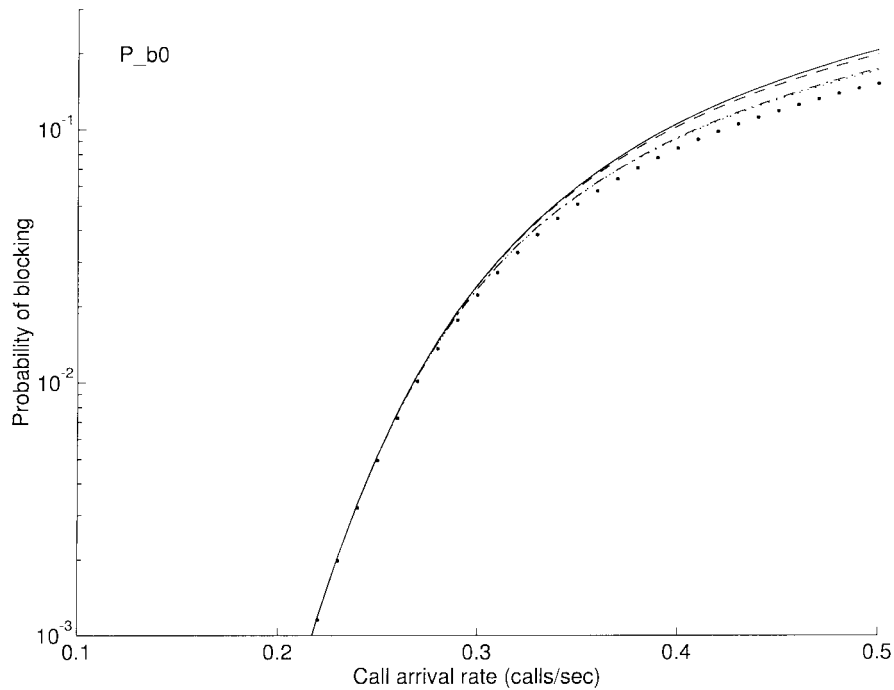


Fig. 3. Probability of blocking in a macrocell for fast mobile stations versus call arrival rate to the area  $\Omega$ ; five cases a)–e) described in the text are shown by: a) solid line, b) point, c) dotted line, d) dash-dot line, and e) dashed line.

- 10) The generation rate of slow mobile stations' handoff traffic in a macrocell is as follows:

$$\lambda'_{sh0} = P'_{h0} \{N(\lambda_{s1} + \lambda_{sh1} + \lambda_{sb1})P_{b1}(1 - P_{b0}) + \lambda'_{sh0}(1 - P_{b0})\}. \quad (17)$$

Note that the probability of handoff failure is the same as the probability of blocking of new calls since there is no prioritization of handoff traffic. We have different session times for different classes of mobile subscribers present in macrocells and microcells, and their resultant session time no longer follows an exponential distribution. However, the probability of call blocking is given by the Erlang loss formula because it does not depend on the distribution of the session time. Invoking this important property, we can use  $\lambda_{t0}/\mu_0 + \lambda'_{t0}/\mu'_0$  and  $\lambda_{t1}/\mu_1 + \lambda'_{t1}/\mu'_1$  as the offered load to macrocell and microcell, respectively, and for  $i = 0, 1$ , write

$$P_{bi} = \frac{\left(\frac{\lambda_{ti}}{\mu_i} + \frac{\lambda'_{ti}}{\mu'_i}\right)^{c_i}}{c_i! \sum_{l=0}^{c_i} \frac{\left(\frac{\lambda_{ti}}{\mu_i} + \frac{\lambda'_{ti}}{\mu'_i}\right)^l}{l!}} \quad (18)$$

where  $\mu_i, \mu'_i$  are given by (3) and (6).

The probability of call loss for fast or slow mobile stations is given as

$$P_{l0} = P_{l1} = P_{b0}P_{b1}. \quad (19)$$

The probability of forced termination (call dropping) for calls in progress from fast or slow mobile stations is approx-

imated as follows:

$$P_{d0} \approx \frac{P_{h0}P_{b0}P_{b1}}{[1 - P_{h0}(1 - P_{b0})]} \quad (20)$$

$$P_{d1} \approx \frac{P_{h1}P_{b0}P_{b1}}{[1 - P_{h1}(1 - P_{b1})]} \quad (21)$$

whereas, when no take-back is considered, the probability of call dropping for calls in progress from fast mobile stations is given as follows:

$$P_{d0} \approx \frac{P_{h0}P_{b0}P_{b1}}{[1 - P_{h0}(1 - P_{b0})]} + \frac{P_{h0}P_{b0}P_{b1}P'_{h1}(1 - P_{b1})}{[1 - P'_{h1}(1 - P_{b1})][1 - P_{h0}(1 - P_{b0})]}. \quad (22)$$

## V. NUMERICAL EXAMPLES AND DISCUSSION

In this section, we present analytical results for a sample case of a two-tier system with two populations of mobile stations of low and high mobility. We assume that the total traffic to the entire area, denoted by  $\Omega$ , follows a Poisson process with the rate  $\lambda$  and the fraction  $p$  of this traffic from slow mobile subscribers. Therefore,  $\lambda_{si} = p\lambda/N$ ,  $i = 1, \dots, N$ , and  $\lambda_{f0} = (1 - p)\lambda$ . We assume four identical microcells overlaid by a single macrocell and  $r_1 = 200$  m and  $r_0 = 400$  m. The average speed of the slow mobile subscribers is considered to be  $V_s = 5$  km/h and of the fast mobile subscribers to be  $V_f = 30$  km/h. We assume  $c_0 = 29$  and  $c_i = 7$ ,  $i = 14$ . The call holding time, as stated in Section II, follows an exponential distribution with mean  $1/\mu = 110$  s.

We consider five cases denoted by a)–e) for comparison as follows.

- *Case a)* This is the entirely flexible system under consideration (i.e., overflow of new or handoff traffic and

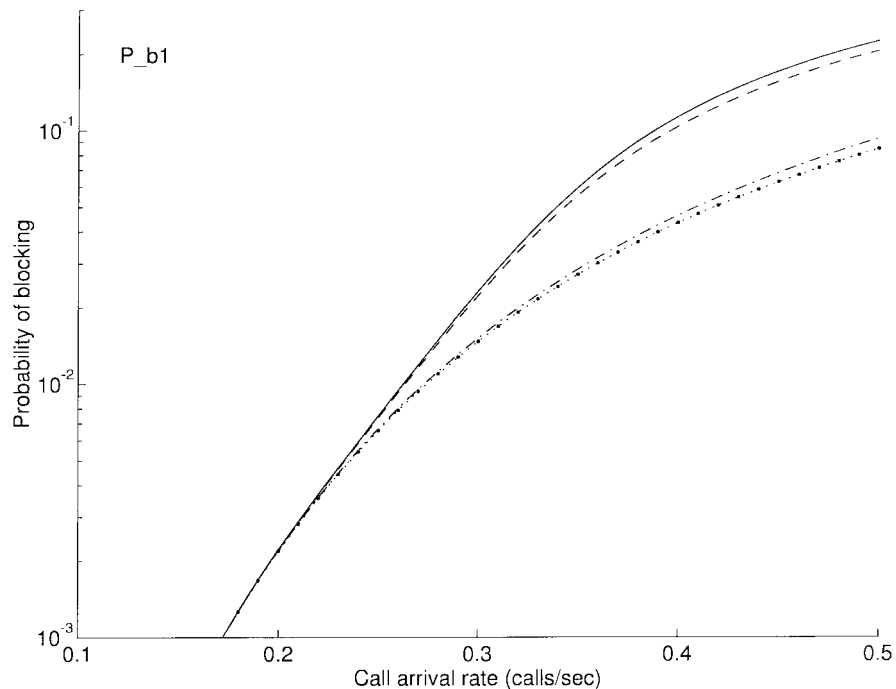


Fig. 4. Probability of blocking in a microcell for slow mobile stations versus call arrival rate to the area  $\Omega$ ; five cases a)–e) described in the text are shown by: a) solid line, b) point, c) dotted line, d) dash-dot line, and e) dashed line.

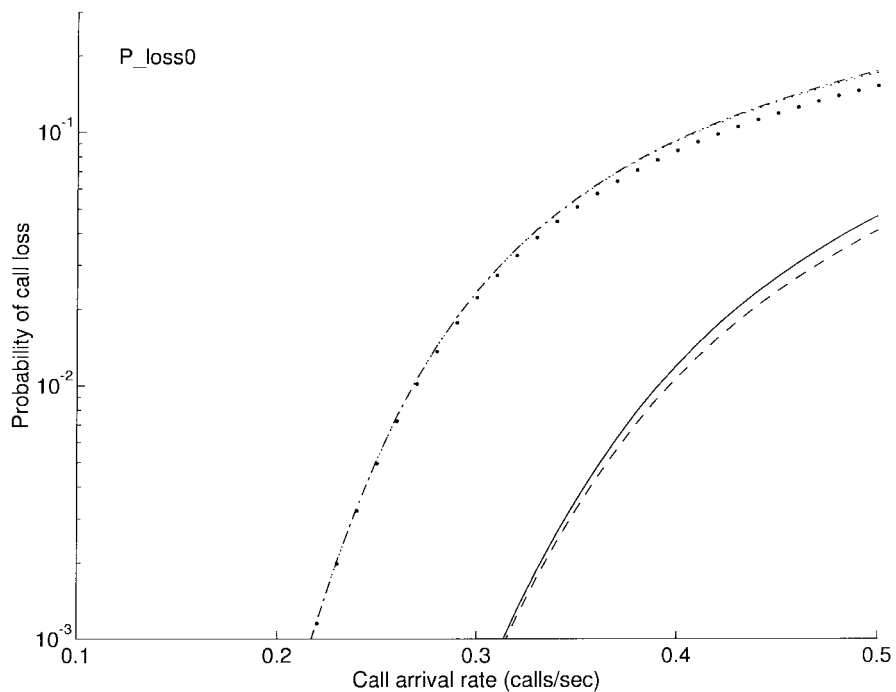


Fig. 5. Probability of call loss for fast mobile stations versus call arrival rate to the area  $\Omega$ ; five cases a)–e) described in the text are shown by: a) solid line, b) point, c) dotted line, d) dash-dot line, and e) dashed line.

- take-back of both slow and fast mobile stations to their appropriate layers).
- *Case b)* A reference system where the two layers are kept completely independent. That is, there is no overflow of new or handoff traffic for either slow or fast mobile stations. Mobile stations are assigned to the appropriate cell layer based on their speeds.

- *Case c)* A system where only overflow of new and handoff traffic for slow mobile stations to a macrocell is allowed. Slow mobile stations initially attempt to obtain a channel in a microcell, and fast mobile stations will only attempt in a macrocell.
- *Case d)* This system enhances case c) with the take-back of slow mobile stations from macrocell to macrocell.

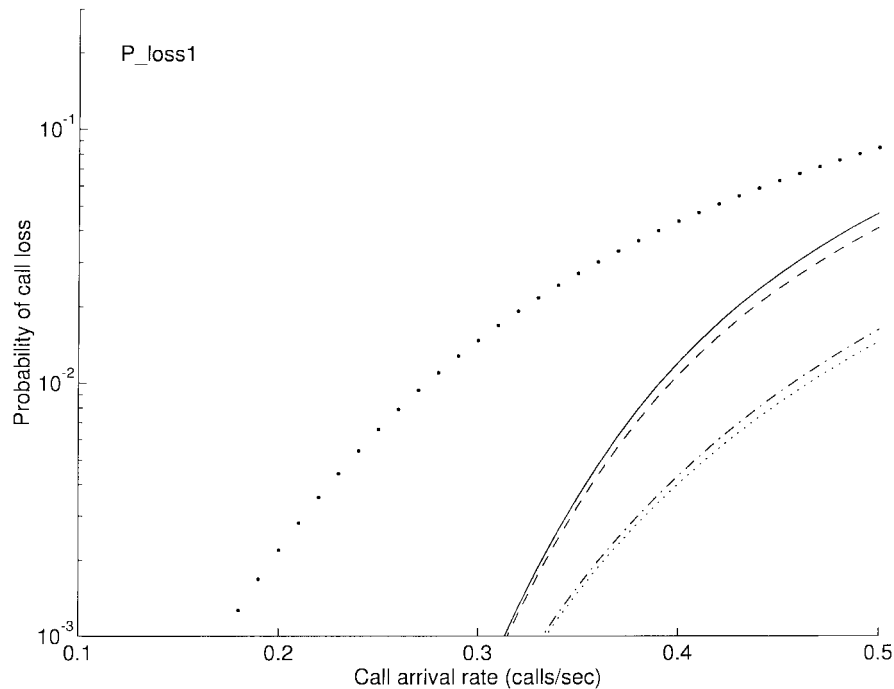


Fig. 6. Probability of call loss for slow mobile stations versus call arrival rate to the area  $\Omega$ ; five cases a)–e) described in the text are shown by: a) solid line, b) point, c) dotted line, d) dash-dot line, and e) dashed line.

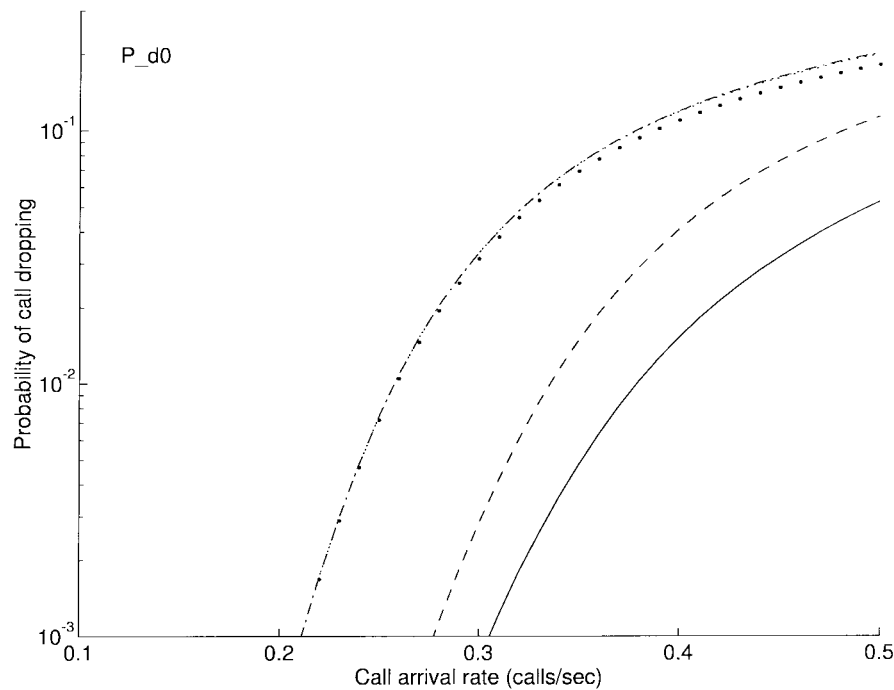


Fig. 7. Probability of call dropping (forced termination) for fast mobile stations versus call arrival rate to the area  $\Omega$ ; five cases a)–e) described in the text are shown by: a) solid line, b) point, c) dotted line, d) dash-dot line, and e) dashed line.

- *Case e)* This system allows the overflow of new or handoff traffic of both slow and fast mobile stations to an alternate layer; however, no take-back of traffic is considered.

As a reference system for the evaluation of the traffic capacity, a system without overflow is chosen. We can readily obtain the relations for offered load due to new and handoff

calls in each layer. Note that in this reference system, slow mobile stations are served by the lower layer only, and call and handoff attempts of slow mobile stations are blocked if all traffic channels in this layer are busy. Correspondingly, fast mobile stations are served only by the upper layer, and call and handoff attempts of fast mobile stations are blocked if there is no idle traffic channel in this layer. We can then use

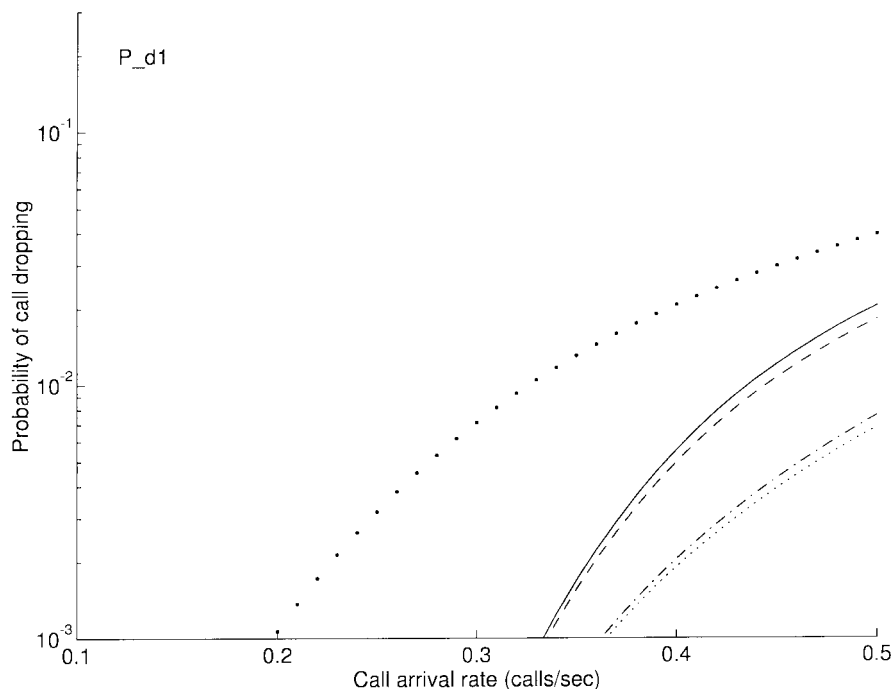


Fig. 8. Probability of call dropping (forced termination) for slow mobile stations versus call arrival rate to the area  $\Omega$ ; five cases a)–e) described in the text are shown by: a) solid line, b) point, c) dotted line, d) dash-dot line, and e) dashed line.

the Erlang B formula and evaluate the probability of blocking for slow and fast mobile stations. The probability of call loss for slow mobile stations will be the same as their blocking probability. Furthermore, we can simply obtain the probability of call dropping (forced termination) for subscribers of each speed class.

In the reference system, the set of traffic channels deployed over the service area is split into two groups for microcells and macrocells. The system capacity can be increased if new call and handoff attempts are allowed to overflow.

If in a first step, only new call and handoff attempts of slow mobile stations are allowed to overflow from the lower to the upper layer. Comparing this with the reference system, we notice that the blocking probability for attempts of slow mobile stations remains the same but the probability of call loss will decrease, while the blocking probability or call loss for attempts of fast mobile stations will increase. Thus, restricting overflow to one direction only does not lead to the desired result.

Increasing the system capacity for both slow and fast mobility user classes requires overflowing capabilities for new and handoff attempts of slow and fast mobile stations in both directions. Additionally, in order to reduce the handoff frequency of fast mobile stations which have been overflowed to the lower layer, calls of slow and fast mobile stations are taken back to their originating layer as soon as traffic channels become available.

The probability of blocking, call loss, and call dropping for slow and fast mobile stations versus call arrival rate to the area  $\Omega$  has been given in Figs. 3–8. We have denoted the five cases a)–e) by the solid line, point, dotted line, dash-dot line, and dashed line, respectively. The results clearly

indicate the advantages in the flexible system. As shown in this figure, the probability of call loss and call dropping diminishes significantly for both classes of subscribers when overflow and take-back are allowed. Furthermore, we observe from Fig. 7 that the probability of call dropping for fast mobile stations is reduced by the take-back process. This can also be verified by simply calculating the expected number of handoffs for this class of calls and comparing this quantity with the no-take-back case.

## VI. CONCLUSIONS

In this paper, we have developed a simple analytical model for a flexible hierarchical system using overflow of new calls, handoff calls, and a take-back mechanism. We have presented the results and have contrasted the gradual improvements in performance (call loss and forced termination) obtained by adding the overflow capability for slow and fast mobile station calls and their handoffs. Additionally, we have shown that the take-back process improves the probability of forced termination for handoffs of fast mobile stations by returning them to a macrocell when a channel becomes available.

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