User Speed Estimation and Dynamic Channel Allocation in Hierarchical Cellular System

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Abstract : **The huge amount of handoffs generated by microcells creates a problem for the future PCN. To alleviate the problem, we propose a hierarchical cellular system which comprises cells of different sizes. Ideally, one would like to use large cells to serve high-mobility users. A challenging issue is to obtain a good estimate of the user speed. In this paper, a simple speed estimation is proposed and based on this estimate one can implement a number of dynamic channel allocation algorithms on such a hierarchical network. A comparative study of these algorithms will be presented based on a detailed simulation model.**

I. INTRODUCTION

One of the technical difficulties in designing a PCN is that the moving speed of its users can vary drastically. On one hand, fast moving users could generate a large amount of handoffs if the cell size is small. On the other hand, micro-cells or even pico-cells are needed in order to handle the high traffic volume in a PCS environment. To circumvent this dilemma, we propose a hierarchical system which aims at seeking a balance between the conflicting objectives of increasing capacity and reducing handoffs.

Our hierarchical system is based on the layered architecture proposed by [1]. A similar model can be found in [2] and [3]. In our system, cells of different sizes coexist. Equal-sized cells are grouped into layers, which overlay on top of one another to form a hierarchy. Since some users may move with very high speed while some others may be, on the other extreme, at a standstill, cells of different sizes are tailored to suit this discrepancy in mobility. Ideally, we would like to assign the slow moving users to a layer with small cells and fast moving ones to a layer with large cells. To achieve this, we present a partition method which divides users into groups according to their speed. However, in real situation, speed of the users is not known. What we can observe is the time a user stays in a cell. Utilizing this information, we design four strategies to determine the suitable cell for the user. In the first two strategies, only the time a user stays in his current cell is used. In contrast to these memoryless strategies, the latter two use the past behaviour of the user to estimate his speed. These strategies will then be compared by a simulation.

II. SYSTEM ARCHITECTURE

A hierarchical system is composed of layers of cells, which are of different sizes. The layers of cells overlay on each other with the largest cells on top. For each cell, there are seven smaller cells underneath, thus forming a hierarchy. To illustrate, a two-layered hierarchical system is shown in Fig. 1.

We will consider a three-layered system thoughout this paper. The term *microcells, normal cells* and *macrocells* will be used to refer to the cells in the corresponding layer. Layer 1 is assumed to be the bottom layer. The radius of cells of layer i is denoted as R_i. By simple geometry, it can be shown that

$$R_{i+1} = \sqrt{7}R_i \qquad (1)$$

How to share the resources among different layers is an important issue. In this paper, we assume the simplest case. Bandwidth are partitioned into disjoint parts and distributed among the layers. This is called *orthogonal sharing* [2]. In each layer, different channel assignment algorithms can be implemented.

When a user moves out of the coverage area of a particular cell site, a handoff is needed. It is possible to switch the call to a cell in a different layer. The term ***handdown, handover*** and ***handup*** are used for the three specific handoff actions.

III. TRAFFIC MODEL

We assume that the arrival of calls form a Poisson process. The interarrival time between calls entering a microcell is exponentially distributed with mean $1/\lambda$. When a new call arrives at a cell, its location is uniformly distributed inside it. Each user is assumed to travel in constant speed v, where v follows an arbitrary distribution.

Each user have an *intended call holding time* Z [1]. The term "intended" is used because a call can be terminated abnormally due to the lack of channels at the instant of handoff. In other words, the actual conversation may be shorter than the intended call holding time. We model Z as an exponential random variable with mean $1/\mu$.

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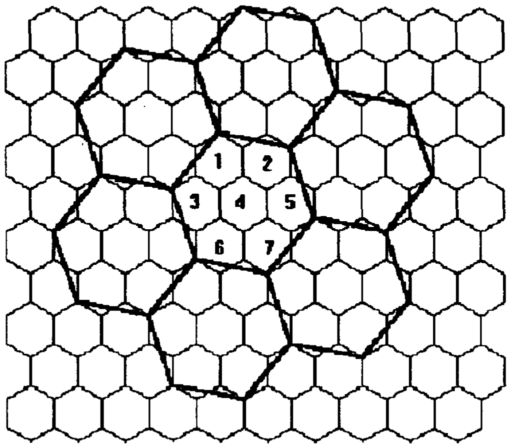

Figure 1: A two-layered hierarchical cellular system

As in [1], the term *cell dwell time* is used to refer to the time a mobile terminal stays in a cell during a call. When a call enters a layer, no matter it is a new call or switched from other layers, its cell dwell time is denoted as X. When a call handover to a neighbour in the same layer, its cell dwell time is denoted as Y. Their distributions are both modeled as exponential but with different means, $1/\zeta_x$ and $1/\zeta_y$ respectively.

For a new call or a call switched from cells in other layers, its starting location is assumed uniformly distributed inside the cell. Approximating the cell as a circle with radius R, the average distance from a random point to the boundary is $8R/3\pi$. Therefore, as in [1], we assume that

$$\zeta_x^{-1} = \frac{8R}{3v\pi} \tag{2}$$

Since a call handed over from neighbouring cells must be at the boundary of a cell, the average distance traversed before leaving the cell is $4R/\pi$. Thus, we assume that

$$\zeta_y^{-1} = \frac{4R}{v\pi} \tag{3}$$

A user will experience a handoff if he moves out of the radio coverage of the base station with which he currently communicates. The faster he travels, probably the more handoffs he experiences. Assume that the user is being served in a layer with cells of radius R and no handup or handdown is occurred. Then, using result from renewal theory, the expected number of handoffs given the speed of the user can be found.

$$E[N|V=v] = \frac{\pi v}{4\mu R}\left(1 + \frac{4\mu R}{3\pi v + 8\mu R}\right) \tag{4}$$

IV. OPTIMAL PARTITION OF USERS

To minimize the average number of handoffs, one should assign the fast-moving users in the large cells, and the slow-moving users in the small ones. The problem is how to find the thresholds to do the partition.

We divide the users into three groups according to their speeds. Let v_α and v_β be the group boundaries ($v_\alpha < v_\beta$) such that the three groups are $[0, v_\alpha)$, $[v_\alpha, v_\beta)$ and $[v_\beta, \infty)$. The groups of users will be assigned to the corresponding layers and we assume that there is no traffic moving among the layers.

Let N_i be the number of handoffs per call in layer i. By equation (4),

$$E[N_i] = \frac{\int_{l_i}^{u_i} h(v, R_i) f_V(v)dv}{\int_{l_i}^{u_i} f_V(v)dv} \tag{5}$$

where l_i and h_i are the boundaries of group i and $h(v,R) = \frac{\pi v}{4\mu R}(1 + \frac{4\mu R}{3\pi v + 8\mu R})$.

Denote the arrival rate of group i users to cells in layer i as λ_i. Then $\lambda_1 + \frac{\lambda_2}{7} + \frac{\lambda_3}{49} = \lambda$ and each λ_i is given by

$$\begin{cases} \lambda_1 = \lambda \int_0^{v_\alpha} f_V(v)dv \\ \lambda_2 = 7\lambda \int_{v_\alpha}^{v_\beta} f_V(v)dv \\ \lambda_3 = 49\lambda \int_{v_\beta}^{\infty} f_V(v)dv \end{cases} \tag{6}$$

Let N be the number of handoffs per call in the system. Combining equation (5) and (6), we have

$$\begin{aligned} E[N] &= \frac{\lambda_1 E[N_1] + (\lambda_2/7)E[N_2] + (\lambda_3/49)E[N_3]}{\lambda} \\ &= \int_0^{v_\alpha} h(v,R_1)f_V(v)dv + \int_{v_\alpha}^{v_\beta} h(v,R_2)f_V(v)dv \\ &\quad + \int_{v_\beta}^{\infty} h(v,R_3)f_V(v)dv \end{aligned} \tag{7}$$

To achieve the goal of minimizing $E[N]$, we want to place more users in the upper layer, because crossing the boundaries of large cells is less frequent. However, this may overload the upper layer. Many calls may be blocked due to the lack of channels and have to be handed down to lower layer. This introduces extra cost. Therefore, it is desirable to keep the blocking probability in each layer small.

In general, any channel assignment strategies for normal cellular system can be implemented in each layer of the hierarchical system. For simplicity, we assume that cells in the same layer have the same number of channels nominally assigned. Denote the number of channels in cells of layer i by m_i.

The blocking probability in layer i is given by the Erlang's B-formula

$$Prob(blocking\ in\ layer\ i) = \frac{\frac{\rho_i^{m_i}}{m_i!}}{\sum_{k=0}^{m_i} \frac{\rho_i^k}{k!}} \tag{8}$$

where $\rho_i = \frac{\lambda_i}{\mu}$.

Therefore, we have to determine v_α and v_β so as to minimize $E[N]$, which subjects to three constraints.

$$\frac{\frac{\rho_i^{m_i}}{m_i!}}{\sum_{k=0}^{m_i} \frac{\rho_i^k}{k!}} \le c \quad \text{for } i = 1,2,3 \tag{9}$$

where c is a constant.

Algorithm : Since the constraints depend on λ_i only and by equation (6), we can rewrite the three constraints as follows.

$$\begin{cases} g_1(\lambda_1(v_\alpha)) \le c \\ g_2(\lambda_2(v_\alpha, v_\beta)) \le c \\ g_3(\lambda_3(v_\beta)) \le c \end{cases}$$

Notice that $g_i(\lambda_i)$ is an increasing function of λ_i.

Step 1 : Increase the value of v_β from 0 until it satisfies

$$g_3(\lambda_3(v_\beta)) \le c$$

and denote this value of v_β as v_β^*.

Step 2 : Increase the value of v_α from 0 until it satisfies

$$g_2(\lambda_2(v_\alpha, v_\beta^*)) \le c$$

and denote this value of v_α as v_α^*.

Step 3 : Check if the following inequality holds.

$$g_1(\lambda_1(v_\alpha^*)) \le c$$

If the inequality holds, the solution is v_α^* and v_β^*. Otherwise there is no feasible solution.

Lemma : *Given v_α, $E[N]$ increases monotonically with v_β. Given v_β, $E[N]$ increases monotonically with v_α.*

Proof : Consider that v_β is increased to v'_β and v_α remains the same. Consequently, $E[N]$ is changed to $E[N']$.

$$\begin{aligned} &E[N'] - E[N] \\ &= \tfrac{\pi}{4\mu}\left[\int_{v_\beta}^{v'_\beta} v\left(\tfrac{1}{R_2} - \tfrac{1}{R_3} + \tfrac{4\mu}{3\pi v + 8\mu R_2} - \tfrac{4\mu}{3\pi v + 8\mu R_3}\right) f_V(v)dv\right] \\ &> 0 \quad (R_2 < R_3) \end{aligned}$$

The second statement can be proved similarly.

□

Proposition : *The solution (v_α^*, v_β^*) obtained by the above algorithm is optimal.*

Proof : If there is no constraint, by the lemma, $v_\alpha = v_\beta = 0$ is the optimal solution. First, consider only the third constraint. Observe that g_3 is an increasing function of λ_3 which in turn is a decreasing function of v_β.

If $g_3(\lambda_3(0)) \le c, v_\alpha = v_\beta = 0$ is still the optimal solution and then let $v_\beta^* = 0$. If the inequality does not hold, v_β is increased in order to decrease g_3 until $g_3 \le c$. Denote this value as v_β^*. Then v_β^* is the smallest value which satisfies the third constraint. By the lemma, $(v_\alpha, v_\beta) = (0, v_\beta^*)$ is the optimal solution if only consider the third constraint.

Next, consider the second constraint. Observe that g_2 is an increasing function of v_β if v_α keeps constant and g_2 is a decreasing function of v_α if v_β keeps constant.

If $g_2(\lambda_2(0, v_\beta^*)) \le c$, the solution $(0, v_\beta^*)$ is still optimal and so let $v_\alpha^* = 0$. If the inequality does not hold, v_α is increased in order to decrease g_2 until $g_2 \le c$. Denote this value as v_α^*. Then v_α^* is the smallest value which satisfies the second constraint given $v_\beta = v_\beta^*$. If now v_β^* is increased to $v_\beta^* + \delta$ ($\delta > 0$), g_2 will increase, thus violating the inequality. Therefore, we have to increase v_α^* in order to compensate for the effect. Hence, $(v_\alpha^* - \epsilon, v_\beta^* + \delta)$ is not a feasible solution ($\epsilon > 0$), i.e. v_α^* is the smallest feasible value of v_α. By the lemma, (v_α^*, v_β^*) is the optimal solution if we consider only the second and third constraint.

Finally comes the first constraint. Notice that g_1 is an increasing function of v_α. If $g_1(\lambda_1(v_\alpha^*)) \le c$, (v_α^*, v_β^*) is the optimal solution. On the other hand, if the inequality does not hold, g_1 has to be decreased which requires the diminishing of v_α. However, it is impossible because v_α^* is the smallest feasible value of v_α. Hence, no feasible solution exists.

□

V. CHANNEL ASSIGNMENT WITH SPEED ESTIMATION

In section IV, users are divided into groups according to their speed. However, this information is not known in real situation. The cell dwell time, which depends on the speed, can be used as a rough estimate. This estimation can be refined if the user's past behaviour is memorised such that when handoff is needed, we can use all the past cell dwell times to make the decision.

As in section III, the i-th cell dwell time T_i is modelled as an exponential random variable with mean equal to $\frac{1}{c_i v}$ where c_i depends on the types of handoff. Now we want to estimate the user's speed given n consecutive cell dwell times. As an example, we assume that the speed V of the users is uniformly distributed between a and b. Two estimators are found as follows.

- Maximum Likelihood (ML) Estimator :

$$\hat{v} = \frac{n}{k}$$

- Minimum Mean-Square Error (MMSE) Estimator :

$$\hat{v} = \frac{n+1}{k} + \frac{a^{n+1}e^{-ka} - b^{n+1}e^{-kb}}{\sum_{i=0}^{n} \frac{n!}{(n-i)!k^i}(a^{n-i}e^{-ka} - b^{n-i}e^{-kb})}$$

where $k = \prod_{i=1}^{n} c_i t_i$.

To minimize the number of handoffs, we would like to assign channels in upper layer to fast-moving users while that in lower layer to slow-moving users. To accomplish this, four strategies are proposed. The first two base only on the most recent cell dwell time t. The first one is proposed by [1] in which only handup is possible. It is modified into strategy 2 which includes also the handdown mechanism. In strategy 3 and 4, decision is made according to the speed estimation of the two estimators.

Strategy 1 : All newly arrived users are placed in the microcell. A threshold parameter τ is defined. When a user moves out of the coverage of a cell, a handoff is needed.

Table 1: Number of Handoffs per call for strategy 1

Arrival Rate (calls/hr/microcell)	25	50	75	100
$\tau = 0$ sec.	5.52	5.53	5.47	5.29
$\tau = 5$ sec.	3.27	3.29	3.27	3.26
$\tau = 30$ sec.	2.10	2.06	2.05	2.02
$\tau = 60$ sec.	1.91	1.83	1.85	1.85

Table 2: Dropping probability for strategy 1

Arrival Rate (calls/hr/microcell)	25	50	75	100
$\tau = 0$ sec.	0	0	0	0
$\tau = 5$ sec.	0	0	0	0.002
$\tau = 30$ sec.	0	0.040	0.073	0.102
$\tau = 60$ sec.	0.004	0.071	0.105	0.133

If his cell dwell time t is larger than τ, he will be handed over to a neighbouring cell. Otherwise, he will be handed up. If a havdover attempt is unsuccessful, a handup attemp is made and vice versa.

Strategy 2 : As strategy 1, all newly arrived users are placed in the microcell. Two threshold parameters τ_1 and τ_2 ($\tau_1 < \tau_2$) are defined. If a user in the normal cell requests for a handoff, his cell dwell time t will be compared with the two thresholds. If $t < \tau_1$, the call will be handed up. If $t > \tau_2$, it will be handed down. Otherwise, it will be handed over. For microcells, calls can only be handed up or handed over. So only τ_1 will be used. Similarly, calls in macrocells cannot be handed up and only τ_2 will be used. If the intended destination cell does not have available channels, handoff to cells in other layers will be attempted.

Strategy 3 : We assume that there is sufficient memory to record all the cell dwell times during the whole life span of a call. ML estimator is used to estimate the speed. The thresholds are predetermined by the algorithm described in section IV.

Strategy 4 : The same as strategy 3 except MMSE estimator is used instead.

VI. SIMULATION MODEL AND RESULTS

In the simulation, a three-layered hierarchical system is used. Totally, there are thirty-six macrocells (6x6), each with radius 2.1 km. For each macrocell, there are seven cells underneath, as shown in Fig.1. If a user moves out of the coverage of the service area, we assume that he has left the system. The traffic model is the same as described in Section III where the average intended call holding time $1/\mu$ is 3 minutes. We assume that there are 40, 20 and 10 channels in each macrocell, normal cell and microcell respectively. The speed of the users is assumed uniformly distributed between 0 km/h and 90 km/h. The offered traffic is uniformly distributed throughout the area concerned.

To investigate the performance of the system, the number of calls lost and the number of handoffs occurred are counted.

Table 1 and 2 shows the number of handoffs and dropping probability for strategy 1. When $\tau = 0$, all users remain in the lowest layer unless there is no available channel. The cells in the upper layers act only as overflow buffer. In this case, the number of handoffs per call is about 5.5. The amount of handoffs is large because almost all of the users stay in the microcells. This result shows the number of handoffs in a system consisting solely of microcells and can be used as a base for comparison.

When τ increases, users will be handed up to the larger cells more easily. This reduces the average number of handoffs. However, as shown in Table 2, the larger the value of τ, the higher the dropping probability. (A call is dropped if it is forced to terminate at times of handoff due to lack of channels) Since there is no mechanism for handdown, inefficient use of resources results and the number of lost calls increases.

We show the number of handoffs under the four different strategies in Fig.2. In strategy 1, we use $\tau_1 = 5$ sec. and in strategy 2, we use $\tau_1 = 30$ sec. and $\tau_2 = 60$ sec. In strategy 3 and 4, we require the blocking probability c in each layer be smaller than 0.01 and apply the algorithm in section IV to find the thresholds for different call arrival rates.

From Fig.2, it can be seen that the system using strategy 1 has the largest number of handoffs. The only way to reduce the amount is increasing the value of τ. However, this will increase the dropping probability also. In fact, using the current parameters, the call loss probability is highest when strategy 1 is used. On the other hand, the loss probability is roughly the same for the other three strategies. This is because all these three strategies can fully utilize the channels in all layers.

Furthermore, the system using strategy 3 or 4 has less average handoffs than that using strategy 2 when the call arrival rate is low. It shows that a better channel allocation can be achieved if speed estimation is employed. However, when the arrival rate becomes high, the benefit diminishes.

It is worth noting that the average number of handoffs given by these strategies is much smaller than that of a system consisting only of microcells, which roughly equals 5.5. However, the capacity of a hierarchical system is smaller. It reveals the fact that the hierarchical system trades its capacity for a reduction in the amounts of handoffs.

VII CONCLUSION

A hierarchical system comprising cells of different sizes is proposed. We have presented a method to partition the users into groups and accomodate different groups into different layers. Four different assignment strategies are compared and we found that handdown is essential for the

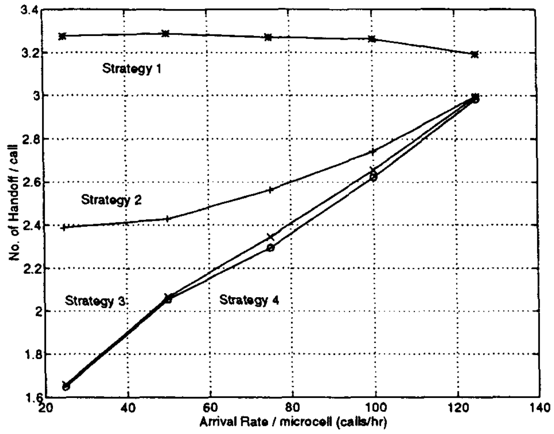

Figure 2: No. of handoffs under different assignment strategies. For strategy 1, we have $\tau = 5$ sec. For strategy 2, we have $\tau_1 = 30$ sec. and $\tau_2 = 60$ sec. For strategy 3 and 4, blocking probability c in each layer is required to be smaller than 0.01

hierarchical system. Besides, the amount of handoffs can be reduced significantly, especially when speed estimation is used at low traffic condition.

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