Dynamic Location Area Management and Performance Analysis

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ABSTRACT A dynamic location area scheme is proposed for cellular networks, in which the size of location areas of a user is dynamically determined according to its current incoming call arrival rate and mobility as the signaling traffic in radio channels reaches the minimum. The protocols and algorithms of the proposed scheme are presented, and its performance is compared with that of the conventional system.

1 Introduction

With an increasing population of mobile subscribers, the signaling traffic of cellular networks is expanding rapidly. Due to the limited radio channel bandwidth, the cell size will be becoming smaller and smaller to increase the reuse of the bandwidth. However, the location update frequency of a mobile user will be increased dramatically[2].

In this paper, we consider the radio channels of signaling network as the key resources, although the switch on signaling network can be another bottleneck in certain situation. To enhance the system performance, many researchers propose using the optimum size of location areas to minimize the signaling traffic [1, 4]. All these previous studies are based on the system with a fixed size of location areas. The fixed size can be optimized such that the combined signaling traffic for location updates and pagings consume the minimal radio bandwidth. When the cell size is given, the optimum size of location areas depends on the arrival rate of incoming calls and mobility of the users. However, different kinds of users may not have the same arrival rate, and furthermore, the arrival rate of a user may not be constant from time to time. Thus, any system with fixed size of location areas is unable to perform optimally for all users.

In this paper, we propose a *dynamic location area scheme*. In this scheme, the size of location areas for a user is not fixed but optimized according to its current arrival rate and mobility. Thus, under the user-variant and time-variant arrival rates, it performs much better than the fixed scheme does. The protocols for dynamic scheme and the algorithms for tracking of the changing rates of a user are presented. Finally, the performance of the proposed system is analyzed.

2 Cost Function of Signaling

In this study, we only consider the signaling cost in *location updates* and *pagings*. Since other signaling traffic does not depends on the size of location areas. A location update occurs as soon as a terminal enters a new location area. When an incoming call attempts to reach a terminal, the network pages the terminal through all base stations in the location areas. Our objective is to reach the minimal bandwidth cost, hence, the maximum radio channel capacity for signaling traffic.

2.1 Radio Bandwidth Cost

In the following discussion, we use square shaped location areas and cell areas. A cell covers an $l \times l$ square area, and a location area covers a square area with $k \times k$ cells ($k = 1, 2, ...$), which is referred as size k location area. The cost of radio bandwidth for the pagings and location updates of a terminal depends on k, length l, the mobility and the incoming call arrival rate of the terminal. Define the following parameters:

a–the arrival rate of incoming (calls/hr/term),
u_k–the location update rate per terminal with size k location areas (upds/hr/term),
C_p–the paging cost of radio bandwidth spent in a cell for a call (bytes/paging/cell),
C_u–the cost for a location update(bytes/upd).

Using $k \times k$ location area, the bandwidth cost for location updates and pagings per terminal per unit time is

$$C(k, a, u_k) = k^2 a C_p + u_k C_u. \quad (1)$$

Let m be the number of outgoing terminals from the location area per unit time, ρ the density of terminals per unit area, v the terminal speed (km/hr). Assuming the mobility model is random movement. From [1], the mean outgoing number of terminals from a cell per unit time is $E[m] = \rho 4klE[v]/\pi$. Thus

$$u_k = E[m]/\rho(kl)^2 = 4E[v]/kl\pi = u_1/k.$$

We normalize C_u to 1 and $C(k, a)/C_u = c(k, a)$, and the *normalized cost function* is

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$$c(k, a, u_1) = k^2 a\gamma + u_1/k, \tag{2}$$

where $\gamma = C_p/C_u$. In the remaining part of this study, we will use the normalized cost function.

2.2 Optimum Size of Location Areas

Define a cost difference equation between the system with size k and the one with size $k-1$ ($k \geq 2$)

$$\Delta(k, a, u_1) = c(k, a, u_1) - c(k-1, a, u_1)$$

$$= \frac{(2k-1)k(k-1)\gamma a - u_1}{k(k-1)}. \tag{3}$$

Proposition 1: Given a, γ and u_1, the optimum k (≥ 1) by which the cost reaches the minimum is

$$k_{opt}(a, u_1) =$$

$$\begin{cases} 1, & \text{if } \Delta(2, a, u_1) > 0, \\ \max\{k : \Delta(k, a, u_1) \leq 0\}, & \text{otherwise.} \end{cases} \tag{4}$$

In the conventional system, the location areas are fixed, whose optimum size is given by $k_{opt}(\bar{a}, \bar{u}_1)$, where $\bar{a}$ is the average arrival rate and $\bar{u}_1$ is the average u_1 over all users. In such a system, the cost of a user is

$$c(k_{opt}(\bar{a}, \bar{u}_1), a, u_1) = k^2_{opt}(\bar{a}, \bar{u}_1)\gamma a + u_1/k_{opt}(\bar{a}, \bar{u}_1).$$

If the arrival rate of a terminal is very different from $\bar{a}$, it may not be served with the minimal cost by the system. To attain better performance, we propose using the optimum size of location areas adapted to each terminal. In this system, the size of location areas of a terminal is dynamically adjusted according to the a and u_1 of the terminal and Proposition 1.

Example 1: (*Model for Microcellular PCN*)

- the size of cells: $150 \times 150\ m^2$ square area,
- the speed of terminals: $v = 5\ km/hr$,
- $\gamma = C_p/C_u = 0.1$,
- $a = 0.6\ calls/hr/terminal$

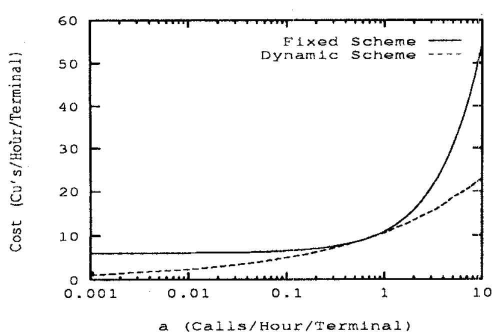

Figure 1: *Normalized bandwidth cost vs. a*

Under the above conditions, the fixed system reaches the minimum bandwidth cost by using $k = 7$. Fig. 1 plots its normalized cost as a function of a when $k = 7$. The cost function of dynamic system is also plotted in Fig. 1. Note that when $a \in (0.51, 0.77)$ both systems pay an equal cost, and outside the region the fixed system pays higher cost than the dynamic one, especially for $a >> 0.77$, or $a << 0.51$ the difference becomes much larger.

Fig. 2 plots the optimum k as a function of a. Note that in low arrival rate region, $k_{opt}(a, u_1)$ changes very rapidly with a.

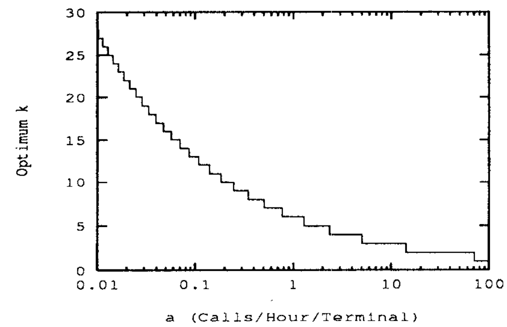

Figure 2: k_{opt} *as function of a*

3 Protocols and Algorithms

In this section, we present the protocols of dynamic system for base stations and mobile terminals and the algorithms for tracking of the call arrival rate and mobility of a terminal.

3.1 Base Station Protocol

An area is covered by a two-dimensional array of cells. Let each cell be identified by an index (x, y), which is a pair of integers indicating in which column and row the cell is located. The base station of a cell periodically broadcasts its index integers (x, y) to inform the mobile terminals in the cell. A terminal will make a decision whether it needs a location update or not according to the received location information.

3.2 Mobile Terminal Protocol

1) When a terminal enters a cell (x_i, y_i) that is in a new location area, it requests a location update. It saves $\lfloor x_i/k \rfloor$ and $\lfloor y_i/k \rfloor$ (where $\lfloor x \rfloor$ is the maximum integer less or equal to x) into two registers.

2) Every time the terminal enters a new cell area of (x_j, y_j), it checks the location information, and if $\lfloor x_j/k \rfloor \neq \lfloor x_i/k \rfloor$ or $\lfloor y_j/k \rfloor \neq \lfloor y_i/k \rfloor$, it requests next location update and resets the register values by $\lfloor x_j/k \rfloor$ and $\lfloor y_j/k \rfloor$.

3) A terminal that needs to change its k value waits until the next location update in order to be in agreement with the system. The value of k for a mobile terminal can be determined either by the terminal or by the system, and the decision side tells the other side the value k during the location update process.

3.3 Paging Process

The network system saves the integers k, $\lfloor x_i/k \rfloor$ and $\lfloor y_i/k \rfloor$ of each terminal during its location update. When an incoming call tries to reach a terminal, the system pages the terminal through the cells at

$(\lfloor x_i/k \rfloor \times k + n, \lfloor y_i/k \rfloor \times k + m)$ for $n = 0, 1, ..., k-1$ and $m = 0, 1, ..., k-1$.

Remark The proposed protocols do not incur much additional overhead. Since in the fixed system, the base stations still need to broadcast their location information, the system still needs to save the location information of all terminals by pointers for possible pagings, and a terminal still needs to save its location information to find out if it enters a new location area. However, in the fixed system, the base stations in the borders of location areas carry all signaling traffic of location updates. Thus, an extra radio bandwidth for signaling is given to all stations, which is wasted in those base stations inside a location area. For example, when $k = 7$, less than 50% of base stations are in the borders. But in the dynamic system, the borders for different size k are overlapped, the traffic load for location updates are more evenly distributed to base stations, and the required bandwidth in each base station for location updates are reduced by 50%. The dynamic system gives a big additional saving.

3.4 Algorithms for Rate Estimation

From Eq. (4), the optimum k depends on the arrival rate a and u_1 of a terminal. The estimations for these two variables can be separated or combined to one.

A. Separate Estimation for a and u_1

Let $\tau = 0$, $\beta > 0$ and A (> 0) be initialized with a proper value (e.g., $\bar{a}$),

(1) The arrival rate of a terminal at time t (≥ 0) is estimated by $\hat{a} = Ae^{-\beta(t-\tau)}$;

(2) If at time t' there is a call termination to the terminal, set $A = Ae^{-\beta(t'-\tau)} + \beta$ and $\tau = t'$, then goto (1).

It can be proved that under Poisson arrival and system equilibrium conditions, the estimator $\hat{a}$ is unbiased, that is $E[\hat{a}] = a$.

Figure 3 shows the transition procedures of A de-

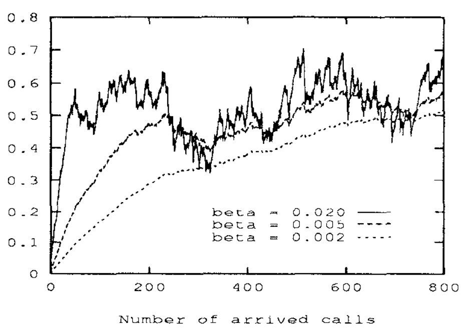

Figure 3: *Variations of A with different β*

termined by the algorithm when $\beta = 0.002$, 0.005 and 0.02. The incoming calls are Poisson with arrival rate 0.5 (*calls/hr*), and the initial A is 0. From the simulation we can see that a larger β gives a shorter transition period and larger fluctuation of A, and a smaller β gives a longer transition period and smaller fluctuation. The tradeoff for β are based on the transition speed and fluctuation of A. For example, using $\beta = 0.02$, the system gives a larger fluctuation in the estimation, $\hat{a} \in (0.3, 0.7)$ as shown in Fig. 3, and k will fluctuate in 7,8 and 9 (compare with Fig. 2). Since these k values fluctuate around the optimum k (here $k_{opt} = 8$) in the range between $(-1, 1)$, the additional bandwidth cost due to the estimation error is small.

To estimate the u_1 of a user we can estimate u_k (upds/hr), where k is the current location area size of the user, then we have $u_1 = k \times u_k$.

B. Combined Estimation Algorithm

Recall Proposition 1, Eq. (4) used to find the optimum k can be rewritten as

$$k_{opt}(a, u_1) = \max\{k : (2k-1)k(k-1) \leq u_1/\gamma a\}, \quad \text{for } k = 1, 2, ... \qquad (5)$$

What we need to estimate here is a/u_1(or u_1/a), then find the optimum k by Eq. (5). a/u_1 gives the measure of number of incoming calls per location update, using size 1 location areas. We estimate its value as follows.

Suppose that a terminal has t_{n-1} call terminations in the period between $(n-1)$-th and n-th location updates, and k_{n-1} is the sizes of location areas used just before the n-th location update. Let $W_n = t_n/k_n$. Using sequence $\{W_n\}$ $(n = 1, 2, ..)$ as input data, we can obtain smooth output values from a low-pass filter. For example, with $0 < \alpha < 1$, the n-th (filtered) estimate of a/u_1 is w_n, given by $w_n = (1-\alpha)w_{n-1} + \alpha W_n$.

4 Performance Analysis

In this section, we analyze the performance of dynamic scheme, and compare it with that of fixed scheme. In the following analysis, the cell size and terminal speeds are the same as that of Example 1.

Example 2 (*User-Variant Arrival Rates*):

Two groups of users have mean arrival rate $a_1 = 0.3$ and $a_2 = 6.0$, respectively. They represent normal users (with a_1) and special users (with a_2) such as taxi drivers. The probability density function (pdf) of a for a normal user is exponentially distributed

$$f_1(a) = \frac{1}{a_1} e^{-a/a_1},$$

and for a special user it is Gaussian distributed

$$f_2(a) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(a-a_2)^2/2\sigma^2},$$

where $\sigma = 0.8$. Assuming that each group contributes 50% of total users, the pdf of arrival rate of a randomly selected user is

$$f(a) = 0.5(f_1(a) + f_2(a)).$$

Assuming u_1 is constant, for given k, the bandwidth cost of the fixed scheme is[1]

$$c_f(k) = \int_0^\infty f(a)c(k,a,u_1)da, \quad (6)$$

and the cost of the dynamic scheme is

$$c_d = \int_0^\infty f(a)c(k_{opt}(a,u_1),a,u_1)da. \quad (7)$$

Fig. 4 plots the mean costs per user per hour for both

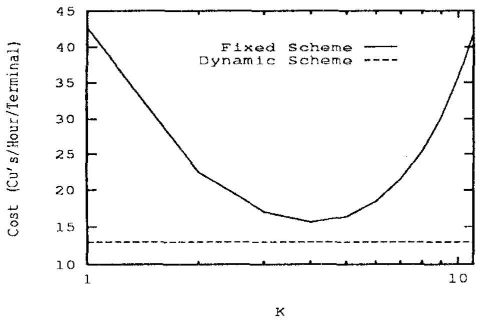

Figure 4: *Normalized cost as function of k*

schemes. Note that the dynamic scheme always performs better than the fixed scheme. Even with the optimum k (=4), the fixed scheme still pays 21% more cost than the dynamic scheme does. Since no matter what value of k is used, the fixed scheme cannot provide the optimum costs for all users. Furthermore, if the design value of k is not 4, the fixed system will pay much higher than 21% in extra bandwidth.

Under the user-variant arrival rate condition, designing a fixed system with optimum size of location areas is a very difficult task. If in the above example the optimum k for the fixed system still can be found globally (but not individually), in the following time-variant arrival rate situation, its optimum k value is totally not obviously to determine for the fixed system.

Example 3 (*Time-Variant Arrival Rates*):
All system parameters are the same as in Example 1, except the arrival rate. Assume that the fixed scheme uses $k = 7$ as the design value, and the arrival rates of users are exponentially distributed with $\bar{a}(= E[a])$, the pdf of a is

$$f(a) = \frac{1}{\bar{a}}e^{-a/\bar{a}}.$$

Consider $\bar{a}$ is time-variant, the cost of the fixed system is given by Eq. (6) using the above $f(a)$ and $k = 7$. Similarly, the cost of the dynamic system is given by Eq. (7) using the new pdf. The costs of both systems in function of $\bar{a}$ are plotted in Fig. 5. We can see that the fixed system always pays higher cost than the dynamic system. The cost gap is smaller only in a small region of $\bar{a}$ (near 0.6), and in other region, the fixed system pays much higher cost, for example, compared with the dynamic system, it pays more than 200% and 150% overhead when $\bar{a} < 0.01$ and $\bar{a} > 10$, respectively. If we design a fixed system with working point in a moderate load region, when a special

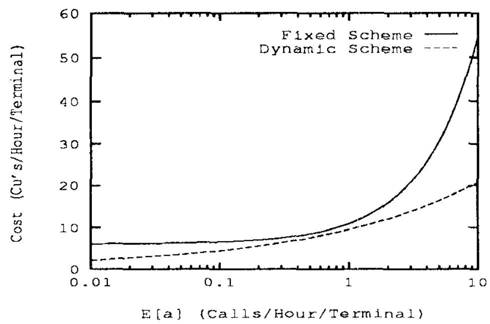

Figure 5: *Normalized cost as function of $\bar{a}$*

event (e.g. convention, accident etc) may suddenly generate unusual high call arrival rates, the signaling radio channels will be congested.

5 Concluding Remarks

In this paper, we proposed a new location registration methodology with dynamic location areas. In the new system, the size of location areas for a mobile terminal is optimized to reach the minimal signaling traffic in the location updates and pagings of the terminal, and the optimum size depends on the incoming call arrival rate and mobility of the terminal. We also proposed the protocols for location updates and pagings. The algorithms that can keep track of the arrival rate and mobility of a terminal are discussed. Our analysis results show that the proposed scheme saves signaling bandwidth significantly when the arrival rates are user-variant or time-variant. Without fixed location borders, the proposed system allocates the signaling burden of location updates more evenly than the fixed system. Thus, as a by-product of the dynamic scheme, the required signaling channel bandwidth of a base station can be reduced further.

References

[1] R. Thomas, H. Gilbert, G. Maziotto, "Influence of the Moving of the Mobile Stations on the Performance of a Radio Mobile Cellular Network," *Proc. of the Third Nordic Seminar on Digital Land Mobile Radio Communications*, Sept. 1988.

[2] K. Meier-Hellstern, E. Alonso, "The Use of SS7 and GSM to Support High Density Personal Communications'," *Proc. of ICC'92*, Chicago, IL pp. 1689-1702, June 1992.

[3] S. Okasaka, S. Onoe, S. Yasuda, A. Maebara, "A New Location Updating Method for Digital Cellular Systems," *Proc. of the 42nd IEEE Vehicular Technology Conference*, Denver (Colorado), pp. 345-350, May 1992.

[4] CCIR Report M/8 (mod. F), "Future Public Land Mobile Telecommunication Systems," *Doc. 8/1014-E*, December 1989.

[1] In general, it is given by a double integration of a and u_1.