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A Dynamic Location Tracking Strategy for Mobile Communication Systems

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Abstract

A major issue for mobile wireless communications is efficient location tracking of mobile users. A common approach is to partition the entire service area into distinct location areas (LAs), each consisting of a group of cells. The LA of a mobile user is updated whenever the mobile user enters a new LA. When an incoming call attempts to reach a mobile user, the system pages the called mobile user in its current LA. We propose a dynamic predictive location management scheme using a continuous-time Markovian mobility model characterized by cell-to-cell transition probabilities. This model and scheme can include geographical limitations of the physical problem. The fact that the movements of most mobile users have some regularity is exploited. The size and shape of LAs are determined dynamically and individually for each mobile user on the basis of gathered statistics and incoming call patterns. This results in the minimum *combined* average cost of location updating and paging signaling for each individual mobile user. In addition, we develop an algorithm to compute the probabilities of finding a mobile user in each cell of its current LA. An optimal multi-step paging algorithm is used to reduce the paging signaling cost. The numerical results demonstrate that the proposed scheme can significantly reduce combined location updating and paging signaling cost.

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1. *Introduction*

The design of efficient location tracking strategies is becoming an increasingly important issue for mobile communications as mobile communication services expand and the subscriber population increases. A commonly used strategy for tracking mobile users is to partition the entire service area into contiguous and distinct location areas, each consisting of a group of cells. The LA of a mobile user is updated whenever the mobile user enters a new LA. When an incoming call arrives, the system pages the called mobile user through the base stations in cells of the mobile user's current LA. Both location updating and paging require a certain amount of wireless bandwidth. Generally, larger LAs allow less frequent location updating for mobile users and thus less location updating signaling traffic. However, the accompanying larger paging areas introduce more paging signaling traffic. Therefore, a tradeoff exists between the location updating cost and the paging cost [1], [2], [4], [5], [8]. A general observation for the desirable LA size is that a larger LA is preferred for a mobile user with high mobility and a low incoming call arrival rate, while a smaller LA is preferred for a mobile user with low mobility and high incoming call arrival rate.

Various location tracking strategies with different objectives have been proposed [1], [3], [4], [5]. In [1], the optimal size of square-shaped LAs for a mobile user is dynamically determined according to the mobile user's current mobility and incoming call arrival rate. A f flow mobility model is used and the signaling traffic for location updating and paging for each mobile user is minimized. This scheme performs better than the fixed scheme in which LA si and position are fixed. A scheme using multi-level LAs that is especially suitable for hierarch cellular structures to track mobile users is presented in [2]. At any given time each mobile use registered at a LA of suitable level. The registered level is dynamically changed according to mobile user's past as well as present mobility. In comparison with fixed LA schemes, the approach allows a more uniform distribution of location updating signaling traffic among the in the service area . It also serves mobile users having a broad range of mobility characteristic without excessive updating signaling traffic.

Three dynamic location update strategies are investigated in [3]: time-based, moveme based, and distance-based strategy. In these strategies, a mobile user performs location updat respectively, according to the time elapsed, the number of cell changes encountered, and the distance traveled (in terms of cells), since the last location updating. It is shown that the distance-based strategy produces the best performance in terms of paging signaling cost per location updating for a mobile user.

A combined distance-based location updating and paging scheme is presented in [4], where a discrete-time Markov model is used to capture the mobility and incoming call arrival pattern of a mobile user. Delay constraints are also considered. The optimal location update threshold distance that results in the minimum costs of location updating and paging is determined by using an iterative algorithm.

Another strategy for location tracking of mobile users is presented in [5]. This scheme exploits the fact that the mobility behavior of many mobile users can be predicted over a certain time period by storing each mobile user's mobility statistics. It is shown that this scheme brings significant savings in wireless resources when mobile users have medium or highly predictable mobility patterns.

The movements of most mobile users have some regularity and a mobile user of given class (pedestrians, vehicles, etc.) may be constrained to follow certain paths. So the configuration of LAs for a mobile user should match that user's movement behavior, street layout, and local topology. For example, one-dimensional LAs are preferred for a mobile user moving along a highway, while grid-shaped LAs are appropriate for a mobile user traveling in a downtown area. Both the preferred size and shape of LAs depend on the individual mobile user and geographical conditions.

In this paper, we propose a dynamic predictive location management scheme. In the scheme, the size of each LA for a mobile user is dynamically determined on the basis of the mobile user's previous and present mobility estimates and current incoming call arrival rate. The shape of each LA for a mobile user is individually and dynamically tailored to match the user's movement and the surrounding geographical conditions. This guarantees that the LAs are suitable for different classes of mobile users such as pedestrians, vehicles, buses, etc. No special prior assumptions about the size and shape of cells and LAs are made so the scheme should be broadly applicable and robust. It differs from those given in [1] and [4], in which, (for two-dimensional cellular systems), the shapes of both cells and LAs were assumed to be either square or hexagonal. The present scheme allows more savings in location updating and paging signaling cost for each mobile user. We use a continuous-time Markovian mobility model to develop a *combined* average cost function for location updating and paging. An iterative algorithm is used to find optimal LAs that result in the minimum *combined* average cost of location updating and paging for each mobile user. An optimal multi-step paging algorithm is used. In addition, we show how the probabilities of finding a mobile user in each cell of the user's current LA can be computed.

2. *Mobility Model*

2.1 Transition Probability Matrix

A good location tracking strategy must consider various factors, including street layout, highway topology, as well as users' mobility and incoming call traffic patterns. We can take a mobile user's movement behavior and relevant geographical factors into consideration by using data table called a transition probability matrix (TPM). For a cellular communication system w m cells, the TPM is an $m \times m$ matrix. Each row corresponds to a cell in which a mobile user currently resides. Each column corresponds to a cell into which a mobile user may move upon leaving the current cell.

The element, p_{ij}, (i, j=1, 2, 3 . . . m), of the TPM, is the probability with which a mob user will next move to cell j upon leaving current cell i. Thus,

$$0 \leq p_{ij} \leq 1 \qquad i, j = 1, 2, 3 \ldots m \qquad (1)$$

$$p_{ii} = 0 \qquad i = 1, 2, 3 \ldots m \qquad (2)$$

$$\sum_{j=1}^{m} p_{ij} = 1 \qquad i = 1, 2, 3 \ldots m \qquad (3)$$

Generally, p_{ij} depends on the current cell i and the cell j as well as the mobile user. The TPM for individual mobile users can be estimated from collected data. In this formulation any two in the service area can be considered to be neighbors regardless of their physical positions. Th

TPM is very useful since it takes into account not only user's movement behavior but also geographical conditions.

2.2 User Mobility and Markovian Model

Suppose the service area is divided into a large number of cells, each served by a respective base station. Mobile users in a cell communicate through the base station of the cell. The base station in each cell periodically broadcasts the cell's identifier on the broadcast channel of the base station. By monitoring the broadcast channel and determining the strongest signal, any mobile user knows the cell in which it is currently located as it travels in the service area. Access to the network will be via the base station of the current cell. Mobile users are free to move and change cells in the service area. We model the mobility of each mobile user by cell changes and refer to such changes as movements from cell to cell.

We assume that a mobile user can change cells at any time instant and that mobile users' movements are probabilistic and independent from one mobile user to another. Specifically the movement of a mobile user is modeled by a continuous-time Markov process whose behavior at state transition instants are governed by the transition probabilities given by the TPM. We treat cells in the service area as states. Cell changes correspond to state transitions of the continuous-time Markov process. This mobility model is summarized below:

- A cell change of a mobile user can occur at any time instant.
- The time interval between successive cell changes is called dwell time of the mobile user in a cell.
- The dwell time in a cell for a mobile user is exponentially distributed with the parameter that depends on the user and the cell.
- At some time instant, a mobile user moves into cell i. After it spends a dwell time in cell i, it will move to one of its neighboring cells, say cell j, with probability p_{ij}.

3. Location Updating and Paging Algorithm

3.1 Location Updating and Location Area

In the proposed scheme, the size and shape of LAs for each mobile user are dynamically changed according to its current mobility and incoming call arrival rate as well as its TPM. It is necessary to provide an algorithm so that each mobile user can identify those cells in its current LA. We assume that each mobile user always maintains a list of cells' identifiers (IDs) of its current LA. Every cell in the service area periodically broadcasts its own cell ID through its broadcast channel. By monitoring the strongest broadcast channel and comparing any newly received cell ID with stored cell IDs, a mobile user can easily determine whether a location update is required. If the newly received cell ID is not on the list of stored cell IDs, a location update is initiated and the list of stored cell IDs is replaced by its new LA. We define this new cell as the *initial* cell of its new LA. The mobile user updates its LA through the base station in the *initial* cell.

The new LA for a mobile user can be computed either by the mobile terminal itself, by the system, or by both. When computing the mobile user's new LA, the *initial* cell for the new LA is used as the initial state of the continuous-time Markov process. Without loss of generality, the *initial* cell is denoted as cell i_0, $1 \leq i_0 \leq m$. So, in the initial state the mobile user resides in cell i_0 with probability 1 and in other cells with probabilities 0. Considering that the mobile user is moving in the service area. Then after one cell change, the mobile user will move to a neighboring cell of the *initial* cell i_0. Since the future state of a Markov process depends only on the present state and state transition probabilities, the probabilities that the mobile user will be in any cell in the future are determined by its present state and the TPM. The probability that the mobile user will be in a specific cell after n cell changes can be obtained given the initial cell i_0 and the TPM. Let $Q^{[n]} =[q_1{}^{[n]}\ q_2{}^{[n]}\ q_3{}^{[n]} .\ .\ .\ .\ q_m{}^{[n]}]$ be the probability distribution of the mobile user's location in the service area immediately after the n-th cell change given that the initial cell is cell i_0. That is, $q_i^{[n]}$ (i=1, 2, 3,... m) is the probability with which the mobile user will be in cell i immediately after the n-th cell change knowing that the mobile user was initially in cell i_0. Let P be the transition probability matrix (TPM), then

$$Q^{[n]} = Q^{[n-1]} P \qquad n=1,\ 2,\ 3, \ldots \qquad (4)$$

where $Q^{[0]} =[q_1{}^{[0]}\ q_2{}^{[0]}\ q_3{}^{[0]} \ldots\ldots q_m{}^{[0]}]$ represents the probability distribution of the mobile user's location in the service area in the initial state. $Q^{[0]}$ has the form

$$Q^{[0]} = [\,0\ 0 \ldots 0\ 1\ 0 \ldots 0\,] \qquad (5)$$

with only the i_0-th element being 1 and all others being 0s (indicating that in the initial state the mobile user resides in the cell i_0 with probability 1 and in other cells with probabilities 0). For mathematical purpose, we also call $Q^{[0]}$ the probability distribution of the mobile user's location in the service area after 0-th cell change. Subsequent conditional probability distributions of the mobile user's location, reckoned on the given *initial* cell i_0, can be obtained using (4).

Another quantity that will be used in the computation of LAs is denoted $s_i^{[n]}$. This is defined as the average number of times that cell i, $1 \le i \le m$, will be visited by the mobile user through n+1 cell changes (the 0-th cell change, i.e, initial state is being counted in the total number of cell changes) given *initial* cell i_0. Let $v_{ij}=1$ if cell i is visited immediately after the j-th cell change, and $v_{ij}=0$ otherwise. Then, the number of times that cell i is visited from the 0-th to the n-th cell change is $\sum_{j=0}^{n} v_{ij}$. Thus

$$s_i^{[n]} = E\left\{\sum_{j=0}^{n} v_{ij}\right\} \qquad i=1,\ 2,\ 3,\ \ldots m \qquad (6)$$

Since the mobile user visits cell i with probability $q_i^{[j]}$ exactly after the j-th cell change, this can be written as

$$s_i^{[n]} = \sum_{j=0}^{n} q_i^{[j]} \qquad i=1,\ 2,\ 3\ \ldots m \qquad (7)$$

Let $f_i^{[n]}$ be the ratio of average number of visits to cell i to the total number of cell changes. Then

$$f_i^{[n]} = \frac{1}{n+1} s_i^{[n]} \qquad i=1,\ 2,\ 3\ \ldots\ m \qquad (8)$$

$f_i^{[n]}$ represents the frequency that the cell i has been visited from the initial state to the n-th cell change. Since $f_i^{[n]}$ is a probability function, we must have

$$\sum_{i=1}^{m} f_i^{[n]} = 1 \qquad (9)$$

We see that (given *initial* cell i_0) the cells in the service area are visited with different probabilities by the mobile user. In order to keep location updating and paging signaling cost we want to include in the new LA those cells that are likely to be visited (that is, those cells having high values of $f_i^{[n]}$ at step n). Thus, when we compute LAs for a mobile user according

$f_i^{[n]}$s, we have a potential LA for the mobile user for each *n*. Generally, the number of cells that are likely to be visited by a mobile user increases with increasing step number *n*, so the number of cells in the potential LA increases with *n*. Since there is a tradeoff between the location updating cost and paging cost for a mobile user, we will choose one of these potential LAs as the new LA for the mobile user. The choice will be made so that *combined* average cost of location updating and paging is minimized. The detailed algorithm will be discussed in section 5. In this way, the size and shape of the resultant LA for a mobile user is dynamically changed.

3.2 Paging Algorithm

When an incoming call arrives, the system pages the called mobile user according to a paging strategy in the cells of the user's current LA. Once the called mobile user is found, the system delivers the call to the mobile user through the base station in the cell in which the mobile user is located. The simplest paging algorithm is to page the called mobile user in all cells of the user's current LA simultaneously. This paging strategy is called simultaneous paging. But, this algorithm requires excessive paging signaling traffic. In order to reduce average paging signaling traffic, multi-step paging algorithms can be used. In multi-step paging, the current LA of a mobile user is partitioned into a number of sub-areas called paging zones according to some algorithm. The system polls one paging zone at a time until the mobile user is found. There are many different multi-step paging algorithms [4], [6], [8], [10]. They use different paging zone creation techniques and page order. *Retry paging* strategies, in which the same cell or same paging zone may be paged more than once in a given search, are sometimes used. Of course, the reduction of average paging signaling traffic by using a multi-step paging algorithm comes at the cost of increased paging delay, since not all cells in the current LA are polled at the same time. We develop an algorithm to calculate the probabilities of a mobile user residing in each cell of its current LA and use some paging zone creation techniques and multi-step paging algorithms.

In the proposed scheme, the size and shape of the LA for a mobile user are dynamically changed. We here suppose that there are r, $1 \leq r \leq m$, cells in the current LA of a mobile user. We renumber the cells from 1 through r with the initial cell of the current LA numbered 1. Let the transition probability matrix of these r cells be

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1r} \\ a_{21} & a_{22} & \cdots & a_{2r} \\ \cdots & & & \\ a_{r1} & a_{r2} & \cdots & a_{rr} \end{bmatrix} \tag{10}$$

in which, a_{ij}, $i, j= 1, 2, 3, \ldots r$, is the probability that the mobile user will next move into cell j upon leaving cell i. The elements of matrix A can be obtained from the mobile user's TPM.

If we consider cells that are not in the current LA to be absorbing states of the Markov process, then the mobile user's movement in the current LA can be modeled by an absorbing Markov process. In this description the mobile user entering an absorbing state means that it leaves the current LA. For an absorbing Markov process, the average number of times a state has been occupied before the process enters an absorbing state can be obtained from its fundamental matrix [13] given initial state. In the fundamental matrix of an absorbing Markov process, the element with indices, (i, j) is the average number of times that state j is visited by the process before the process enters an absorbing state, given that the process was initially in state, i. The mobile user's movement in the LA can be modeled as an absorbing Markov process. Let B be fundamental matrix of the absorbing Markov process. Then

$$B=(I-A)^{-1} \tag{11}$$

where I denotes a unity $r \times r$ matrix. The resultant B has the form

$$B= \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1r} \\ b_{21} & b_{22} & \cdots & b_{2r} \\ \cdots & & & \\ b_{r1} & b_{r2} & \cdots & b_{rr} \end{bmatrix} \tag{12}$$

Therefore, the element b_{1j}, $1 \le j \le r$, is the average number of times that cell j has been visited the mobile user before the mobile user leaves the current LA given the initial cell which was numbered 1 in the matrix A. So, the average number, $\overline{N}$, of cell changes needed for the mobile user to leave the current LA is

$$\overline{N} = \sum_{j=1}^{r} b_{1j} \tag{13}$$

Let $\overline{T_{dj}}$ denote the average dwell time of the mobile user in cell j, $1 \le j \le r$,. Then the average time interval that the mobile user spends in the LA is

$$\overline{T_D} = \sum_{j=1}^{r} (b_{1j} . \overline{T_{dj}}) \tag{14}$$

This is called the dwell time of the mobile user in the LA.

Let α_j represent the average fraction of time that the mobile user resides in cell j during the mobile user's dwell time in the LA. Then

$$\alpha_j = \frac{b_{1j} . \overline{T_{dj}}}{\overline{T_D}} = \frac{b_{1j} . \overline{T_{dj}}}{\sum_{i=1}^{r} (b_{1i} . \overline{T_{di}})} \qquad j = 1,2,3 \ldots r \tag{15}$$

in which, α_j is the probability with which the mobile user can be found in cell j knowing only that the mobile user is in the LA and the initial cell numbered 1. We call α_j the residing probability of the mobile user in cell j in the LA.

Many paging zone creation techniques and multi-step paging strategies can be used in the system to reduce paging signaling traffic when the residing probability distribution of the mobile user in the cells of the current LA is known. In the proposed scheme, we use the optimal k-step paging algorithm proposed in [6] which is optimal in the sense of minimizing average paging cost. However, the needed probabilities are determined according to our equation (15). In the algorithm, the cells in the current LA are partitioned into k disjoint sub-areas ($A_1, A_2, \ldots A_k$) such that the average paging cost is minimized. This algorithm is described below:

- First, we sort the r cells of the current LA in non-increasing order of residing probability for the mobile user. Without loss of generality, we assume that the residing probabilities are arranged in non-increasing order α_1, $\alpha_2, \ldots$ α_r.
- Then, assume at some step of the algorithm, A_i includes t_i cells, i=1, 2, . . . k. That is the cells 1, 2, . . .t_1 are in sub-area A_1, cells t_1+1, t_1+2, . . . t_1+t_2 are in sub-area A_2, etc. (Initially, let $t_1 = t_2 = \ldots$ t_{k-1}=1 and t_k=r-k+1). Let $\pi_i = \sum_{j \in A_i} \alpha_j$, $m_i = \sum_{j=1}^{i} t_j$, i=1, 2. . . k. The condition for moving a cell with residing probability α_{m_j+1} from sub-area A

to A_j is $\alpha_{m_j+1} \geq \frac{\pi_j}{t_{j+1}-1}$. Perform this procedure until no cell meets this condition.

- When an incoming call arrives, the system pages the called mobile user in the sub-areas $A_1, A_2, \ldots A_k$ sequentially until the mobile user is found.

4. *Location Updating and Paging Cost*

We will first consider the average location updating cost and paging cost separately. Then a *combined* average cost function of location updating and paging will be given.

A location updating signal is generated whenever a mobile user enters a new LA. Recall that $\overline{N}$ is the average number of cell changes needed for a mobile user to leave its current LA and let the average cell dwell time of the mobile user over all cells in the LA be $\overline{T_d}$. Then

$$\overline{T_d} = \frac{\sum_{j=1}^{r}(b_{1j}.\overline{T_{dj}})}{\sum_{j=1}^{r} b_{1j}} = \frac{\overline{T_D}}{\overline{N}} \tag{16}$$

So, location updating occurs at average rate $(1/\ \overline{N}.\overline{T_d}\ )$. Let L_c be the signaling cost for a mobile user to perform single location update (in term of messages transmitted for a single location update). L_c generally depends on the location updating mechanism. So, the average location updating cost of a mobile user per unit time C_u is:

$$C_u = \frac{L_c}{\overline{N} \cdot \overline{T_d}} \tag{17}$$

When an incoming call attempts to reach a mobile user, the system pages the mobile user in cells of the user's current LA. Let λ be the incoming call arrival rate of the mobile user, and P is the signaling cost per page in a cell in term of messages transmitted. Let $\overline{M}$ be the average number of cells polled to find the mobile user in the current LA. Generally, $\overline{M}$ depends on the paging algorithm, the residing probability distribution, and r, the number of the cells in the current LA. For the optimal k-step paging algorithm used in the scheme, $\overline{M}$ can be obtained as follows

We assume that there are $t_1,\ t_2, \ldots\ t_k$ cells ($t_1 + t_2 + \ldots + t_k = r$) in the sub-areas $A_1, A_2, \ldots A_k$, respectively. Let the residing probabilities of the mobile user in sub-areas A_1 , $A_2, \ldots A_k$, be $\beta_1, \beta_2, \ldots \beta_k$, respectively, and $t_0 = 0$. Then

$$\beta_j = \sum_{i \in A_j} \alpha_i \qquad j=1,\ 2,\ 3, \ldots k \tag{18}$$

Where α_i is the residing probability of the mobile in cell *i*. The average number of cells, $\overline{M}$ that are polled to find the mobile user is given by

$$\overline{M} = \beta_1 \cdot t_1 + \beta_2 \cdot (t_1 + t_2) + \cdot \quad \cdot + \beta_k \cdot (t_1 + t_2 + \ldots + t_k) = \sum_{i=1}^{k} \beta_i \cdot \sum_{j=1}^{i} t_j \tag{19}$$

The average paging signaling cost for the mobile user per unit time, C_p, is

$$C_p = \lambda \cdot \overline{M} \cdot P_c \tag{20}$$

The *combined* average cost for location updating and paging for a mobile user per unit time C is

$$C = C_u + C_p \tag{21}$$

In the proposed scheme this cost function will be used to find the optimal LA. In this way the *combined* average cost of location updating and paging for a mobile user is minimized.

5. Location Update Mechanism and Optimal LA

A main objective of the proposed scheme is to reduce the signaling cost for location updating and paging. This is accomplished by using a TPM that takes into consideration many factors that influence the mobility of mobile users, so that these factors are reflected in the probability calculations that are inherent in the scheme. In the proposed scheme, each mobile user keeps a list that contains the cell IDs of its current LA. If a mobile user enters a new cell whose ID is not on the list, this cell becomes the initial cell of a new LA and a location update initiated. We also assume that each mobile terminal records its dwell time in each cell it has visited in the LA, so that the mobile user can calculate its average cell dwell time $\overline{T_d}$ for each This initial cell and the average cell dwell time $\overline{T_d}$ in the last LA will be used in the computa of the mobile user's new LA. In this way, the average cell dwell time $\overline{T_d}$ in the last LA is use estimate of present mobility. The computation can be performed either by the system or by the mobile terminal itself or by both. After computation, a list of cells is assembled to be the new If the computation is done on only one side, that side must transmit the list of cells to the othe side. The mobile user updates its LA by replacing the old list with the new one. The system also must store the new LA of the mobile user to keep the track of the mobile user for possible pages.

Generally, $\overline{N}$ in (17) and $\overline{M}$ in (20) increase with r, the number of cells in the LA, increasing, so, the average location updating cost for the mobile user per unit time, C_u, decreases with r increasing, while the average paging cost, C_p, increases with r increasing. Thus, the *combined* average cost function, C, of location updating and paging for the mobile user may have a local minimum for some r. In the following, we present an algorithm to compute its optimal LA for given conditions.

Assume we have empirically defined a set of threshold probabilities ε_1, ε_2, ... ε_n... (for example, 0.1, 0.05, 0.02, 0.01..., respectively). The computing procedure is as follows:

- Initialization. Let n=0, compute the *combined* average cost of location updating and paging, $C(0)$, of the LA that includes only the initial cell.
- Let $n = n+1$, and compute $f_i^{[n]}$. Select those cells with $f_i^{[n]} \geq \varepsilon_n$ as a potential LA and compute the *combined* average cost of location updating and paging, C(n), for the potential LA.
- If the *combined* cost $C(n) \geq C(n-1)$, then the procedure terminates. The cells with $f_i^{[n-1]} \geq \varepsilon_{n-1}$ at (n-1)th step form new LA for the mobile user.
- Otherwise the procedure continues with n=n+1 step until the optimal LA is found.

The resultant LA from the procedure outlined above must minimize the *combined* average cost of location updating and paging for the mobile user for a given set of threshold probabilities. Since the resultant LA is optimal only for a given set of threshold probabilities, we also say it is sub-optimal for the mobile user. Generally, it is difficult to find a global optimal LA for a mobile user since we have to compute optimal LAs for all possible sets of threshold probabilities.

6. Numerical Results

The performance of the proposed scheme depends greatly on actual TPMs. In order to evaluate the proposed scheme, we assume the service area is divided into hexagonal cells of the same size. Each cell has six neighbors. A mobile user of a given class can move to the neighboring cells upon leaving the current cell with the probabilities p_1, p_2, p_3, p_4, p_5, p_6 respectively. Generally, these six probabilities are not the same and also depend on the current cell. For numerical purposes, we assume that the cellular system is homogeneous. So the set of six probabilities is the same in all cells (note, however, that generally $p_1 \neq p_2 \neq p_3 \ldots \neq p_6$). The vehicular mobile users have the same set of six probabilities, pedestrian mobile users have another set of six probabilities. This is reasonable because the vehicular traffic may be constrained to follow certain paths, one-way streets, etc. while pedestrian users move more slowly but may have different paths and traffic patterns.

6.1. Average Paging Cost of Multi-Step Paging Algorithm

In the scheme, when an incoming call arrives, the system pages the called mobile user using an optimal multi-step paging algorithm. This allows a great savings in paging traffic in comparison with simultaneous paging in which all cells in the current LA are polled simultaneously. Fig. 1 shows the average paging signaling cost needed to find the mobile user in its current LA as the number of paging steps varies. Here we assume p_1=0.3, p_2=0.1, p_3=0.1, p_4=0.3, p_5=0.1, p_6=0.1. For a given initial cell, the LA is chosen to have 27 cells. As shown, average paging signaling cost decreases as the number of paging steps increases. The average paging signaling cost is the highest when the 1-step paging algorithm (simultaneous paging algorithm) is used. The reduction in the average paging signaling cost is very significant even 2-step or 3-step paging algorithm. The gain is not much when the number of paging steps continues to increase. This suggests that a paging algorithm with more steps is not advantageou. It is intuitive that mobile users with more predictable (less random) mobility pattern can achiev more savings in average paging signaling cost when an optimal multi-step paging algorithm is employed.

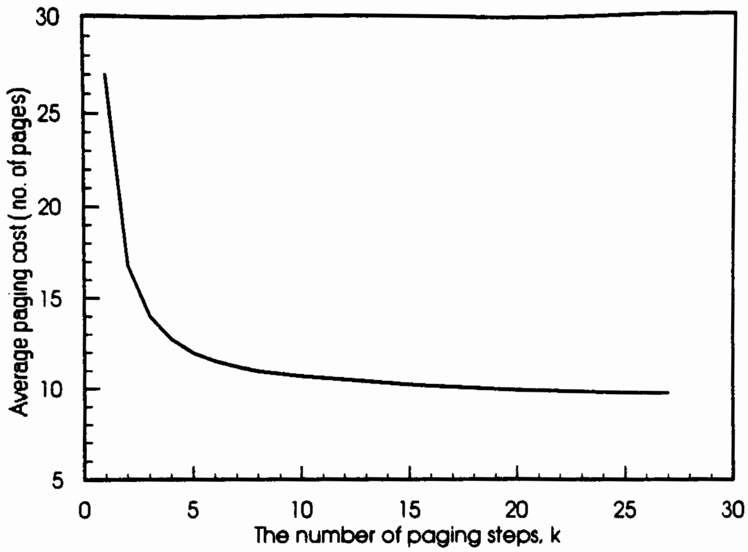

Fig.1 Average paging cost for optimal multi-step paging.

Parameters: p_1=0.3, p_2=0.1, p_3=0.1, p_4=0.3, p_5=0.1, p_6=0.1 and

ε_1=0.1, ε_2=0.05, ε_3=0.02, ε_4=0.01, ε_5=0.005.

6.2 Optimal LA Size and Incoming Call Arrival Rate

In the proposed scheme, the size and shape of LAs for a mobile user are dynamically determined according to the mobile user's present mobility and incoming call arrival rate as well as the mobile user's TPM. Fig. 2 shows optimal LA size for a mobile user decreases with incoming call arrival rate λ. It can be seen that the mobile user tends to have larger optimal LA when optimal 2-step paging strategy is used compared to the case when 1-step paging algorithm used. This is because less paging signaling traffic is needed when 2-step paging is used in paging algorithm. Here, we assume p_1=0.4, p_2=0.05, p_3=0.05, p_4=0.4, p_5=0.05, p_6=0.4. The average cell dwell time $\overline{T_d}$ =0.1 hour, and the ratio $L_c / P_c = 4$. This is reasonable since the location updating is more costly than paging [1], [4].

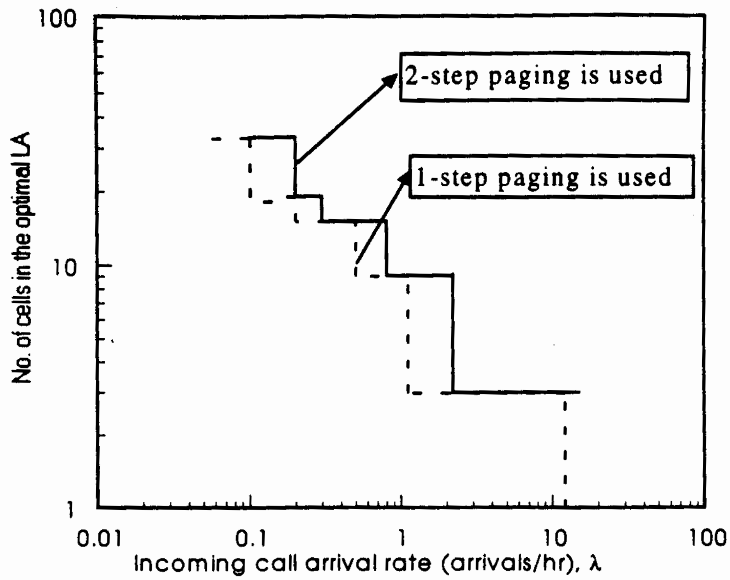

Fig.2 Number of cells in the optimal LA for different incoming call arrival rates.

Parameters: p_1=0.4, p_2=0.05, p_3=0.05, p_4=0.4, p_5=0.05, p_6=0.05. ,

ε_1=0.1, ε_2=0.05, ε_3=0.02, ε_4=0.01, ε_5=0.005, $\overline{T_d}$ = 0.1 and L_c/P_c=4.

6.3 Comparison of the Proposed Scheme On a Per-User Basis

In this section, we will compare the proposed scheme with the scheme in which LAs are hexagonal with the initial cell at the center of LAs, and the position and size of LAs are dynamically changed according to the user's mobility and incoming call arrival rate. We call this scheme the scheme with hexagonal LAs. Fig. 3 shows the location update rates of a mobile user for each scheme as the number of cells in the LA is varied. For this figure, the following parameters were chosen: $\overline{T_d}$ is 0.1 hour and p_1=0.4, p_2=0.05, p_3=0.05, p_4=0.4, p_5=0.05, p_6=0.05. It can be seen that the proposed scheme outperforms the other. This is because, in the proposed scheme the shape of the LAs for a mobile user are individually tailored to match the user's movement behavior and geographical conditions. It is intuitive that if the mobility pattern of the mobile user is less random, the better the proposed scheme performs compared to the scheme with hexagonal LAs. Even with the most random mobility pattern, i.e., $p_1 = p_2 = p_3 = p_4 = p_5 = p_6 = 1/6$, the proposed scheme has the same performance as the scheme with hexagonal LAs since the shape of LAs in the proposed scheme is tailored to be hexagonal for this mobility pattern.

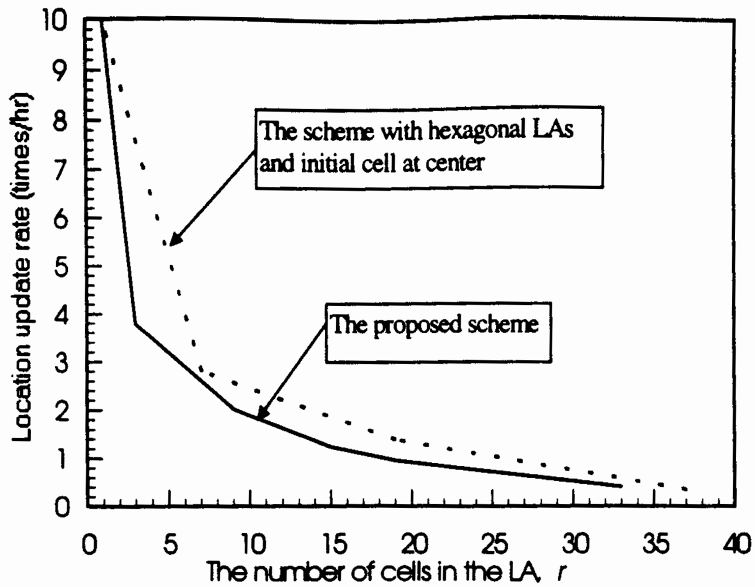

Fig. 3 Average location update rate as the size of LA varies.

Parameters: p_1=0.4, p_2=0.05, p_3=0.05, p_4=0.4, p_5=0.05, p_6=0.05,

ε_1=0.1, ε_2=0.05, ε_3=0.02, ε_4=0.01, ε_5=0.005, and $\overline{T_d} = 0.1$.

6.4 Comparison of the System Performance of the Proposed Scheme and the Scheme with Hexagonal LAs

In order to compare the system performance of the proposed scheme with that of the scheme with hexagonal LAs, mobile users have been classified into two groups, pedestrian and vehicular users. Pedestrian users are assumed to have a more random mobility pattern (for pedestrian users, p_1=0.3, p_2=0.1, p_3=0.1, p_4=0.3, p_5=0.1, p_6=0.1), while vehicular users ha less random mobility (for vehicular mobile users, p_1=0.4, p_2=0.05, p_3=0.05, p_4=0.4, p_5=0.0 p_6=0.05). Each group contributes 50% of total users. We also assume that the average cell dw time of pedestrian and vehicular users are 0.4 and 0.1 hour respectively, and L_c / P_c =4. For simplicity, a simultaneous paging algorithm is used. We assume that the probability density function of incoming call arrival rate λ for all mobile users including pedestrian and vehicular users has a Gaussian distribution with $\overline{\lambda}$ and variance σ^2. Because the incoming arrival rate mobile user can never be negative or infinite, we consider λ as a truncated Gaussian in which density is non-zero only in the interval [0, λ_{max}]. Normalizing λ such that the area under its curve equals 1, we obtain the pdf of λ

$$f(\lambda)=\frac{1}{\Delta\cdot\sqrt{2\pi\sigma^2}}e^{-(\lambda-\bar{\lambda})^2/2\sigma^2} \qquad \lambda\in[0,\quad \lambda_{max}] \qquad (22)$$

in which the normalizing factor, Δ, is

$$\Delta=\int_0^{\lambda_{max}}\frac{1}{\sqrt{2\pi\sigma^2}}e^{-(\lambda-\bar{\lambda})^2/2\sigma^2}d_\lambda \qquad (23)$$

Since the *combined* cost function (21) is the function of λ, $\overline{T_d}$, and optimal r , while optimal r is the function of λ, $\overline{T_d}$, the *combined* cost C can be written as

$$C=C(\lambda,\ \overline{T_d},\ r(\lambda,\overline{T_d})) \qquad (24)$$

The normalized *combined* cost of the proposed scheme for a given class of mobile users is

$$C_t=\int_0^{\lambda_{max}}f(\lambda)\cdot C(\lambda,\overline{T_d},r(\lambda,\overline{T_d}))d_\lambda \qquad (25)$$

The scheme with hexagonal LAs has the same form normalized *combined* cost function as the proposed scheme.

The performance for each of these two schemes is plotted in Fig. 4. It is seen that the proposed scheme with dynamic location area is always better than the scheme with hexagonal LAs. Here, the parameters were chosen such that $\lambda_{max}=10$ arrivals/hr and σ=1.

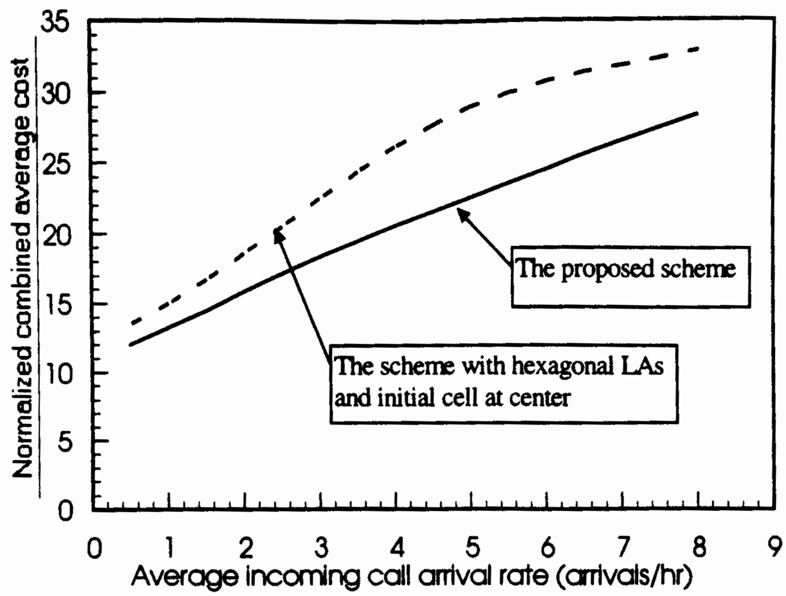

Fig. 4 Normalized *combined* cost of location updating and paging.

Parameters: ε_1=0.1, ε_2=0.05, ε_3=0.02, ε_4=0.01, ε_5=0.005,

$\lambda_{max} = 10$ arrivals/hr, σ=1, L_c/P_c=4.

For vehicular users: p_1=0.4, p_2=0.05, p_3=0.05, p_4=0.4, p_5=0.05, p_6=0.05, and $\overline{T_d} = 0.1$.

For pedestrian users: p_1=0.3, p_2=0.1, p_3=0.1, p_4=0.3, p_5=0.1, p_6=0.1 and $\overline{T_d} = 0.1$.

7. Conclusions

A dynamic predictive location management scheme is proposed that is especially suitab for mobile users whose movements have some regularity and predictability. In this scheme, the size and shape of LAs are tailored so that the *combined* average cost of location updating and paging for a mobile user is minimized for a given a set of threshold probabilities. Numerical results show that the proposed scheme can reach a significant reduction of the combined avera cost of location updating and paging compared to other schemes.

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