Chapter

TERMINAL PAGING WITH FAST SPEED, LOW COST AND HIGH QUALITY OF SERVICE

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Abstract

Dynamic location management for a mobile terminal is a key problem in wireless communication networks. There are three fundamental performance and cost issues in terminal paging. The first issue is the speed (i.e., time delay) of terminal paging. The second issue is the cost (i.e., the number of cells paged) of terminal paging. The third issue is the quality of service (QoS), i.e., the probability that a mobile terminal is found. It is clear that it is hard and a challenge to achieve fast paging speed, low paging cost, and high QoS simultaneously. The motivation of this chapter is to show that it is possible to achieve fast paging speed, low paging cost, and high QoS simultaneously. We propose the method of *aggressive paging*, which essentially is to page an area smaller than the paging area, and to have the fastest speed (i.e, the shortest time delay), low cost, and high QoS. Such simultaneous achievement of high performance and low cost are obtained based on our knowledge of the location distribution of a mobile terminal in a paging area. To the best of the author's knowledge, such a paging method has not been reported in the existing literature.

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1. Introduction

Dynamic location management for a mobile terminal is a key problem in wireless communication networks. The problem includes two components, i.e., location update and terminal paging. For both of them, various methods have been proposed and their performance has been analyzed. Location update methods include *movement-based location management schemes* (MBLMS), *distance-based location management schemes* (DBLMS), and *time-based location management schemes* (TBLMS). Two different kinds of paging methods have been studied in the literature, i.e., the simple paging method and various selective paging methods.

There are three fundamental performance and cost issues in terminal paging (see Table 1). The first issue is the speed (i.e., time delay) of terminal paging. The simple paging method has the fastest speed and the shortest time delay, i.e., a mobile terminal can be found in one round of paging. A selective paging method has slow or the slowest speed and long or the longest time delay, i.e., several or even the maximum rounds of paging are required to find a mobile terminal. Typically, the number of rounds can be as large as the number of rings or even the number of cells in a paging area.

The second issue is the cost (i.e., the number of cells paged) of terminal paging. The simple paging method needs to page all cells in a paging area, and thus has the highest cost, i.e., the greatest number of cells paged. A selective paging method (e.g., progressive paging, ring paging, cell paging [37]) needs to page a small or the smallest number of cells on the average, and thus has low or the lowest expected cost, although the cost can still be as high as that of the simple paging method in the worst case.

The third issue is the quality of service (QoS), i.e., the probability that a mobile terminal is found. In an MBLMS or a DBLMS, the QoS of both simple paging and selective paging is 100%, i.e., it is guaranteed that a mobile terminal can be found. For a TBLMS, to guarantee 100% QoS, the cost will be infinite in the worst case, since a mobile terminal can be arbitrarily far away from the cell where the last location update is performed. Therefore, any realistic terminal paging method for a TBLMS can only provide high QoS, i.e., high probability that mobile terminal is found.

Table 1. Comparison of Various Paging Methods

Method	Speed (time delay)	Cost	QoS
Simple	Fastest (shortest)	Highest	100% or high
Selective	Slow/Slowest (long/longest)	Low/lowest	100% or high
Aggressive	Fastest (shortest)	Low	High

From the above discussion, it is clear that it is hard and a challenge to achieve fast paging speed, low paging cost, and high QoS simultaneously. While both the simple paging method and a selective paging method can achieve high QoS, the simple paging method suffers from the highest cost of paging, while a selective paging method suffers from slow or the slowest speed of paging. For a TBLMS, achieving higher QoS implies slower speed and/or higher cost.

The motivation of this chapter is to show that it is possible to achieve fast paging speed, low paging cost, and high QoS simultaneously. We propose the method of *aggressive paging*, which essentially is to page an area smaller than the paging area, and to have the fastest speed (i.e, the shortest time delay), low cost, and high QoS. Such simultaneous achievement of high performance and low cost are obtained based on our knowledge of the location distribution of a mobile terminal in a paging area. To the best of the author's knowledge, such a paging method has not been reported in the existing literature.

The relationship between aggressive paging and progressive paging is analogue to the relationship between a Monte Carlo algorithm (which has guaranteed fast execution time, but does not guarantee to find a solution, yet finds a solution with high probability) and a Las Vegas algorithm (which guarantees to find a solution, but does not guarantee fast execution time, yet has fast expected execution time). The aggressive paging method has guaranteed fastest paging time and low paging cost, but does not guarantee to find a mobile terminal, yet finds a mobile terminal with high probability. A progressive paging guarantees to find a mobile terminal, but does not guarantee fast paging speed and low paging cost, yet has fast expected speed and low expected cost.

We would like to mention that while Monte Carlo algorithms and Las Vegas algorithms are randomized, both aggressive paging and progressive paging methods are deterministic and not randomized. However, their relationship is analog to Monte Carlo vs. Las Vegas algorithms. Randomness comes from the input, i.e., the location distribution of a mobile terminal in a paging area.

The rest of the chapter is organized as follows. In Section 2, we review related research. In Section 3, we describe our models. In Section 4, we discuss location distribution. In Section 5, we present our aggressive paging method. In Section 6, we show performance data. In Section 7, we compare the costs of various location management schemes. In Section 8, we conclude the chapter.

2. Related Research

The design and analysis of any dynamic location management scheme depend on a mobility model of mobile terminals. Various mobility models have been proposed in the literature, including the shortest distance mobility model [1, 2], the fluid flow model [6, 11], the big move and the random walk models [13], the user mobility pattern scheme [15], the cell coordinates system [41], the isotropic diffusive motion model [44], one-dimensional Markov chains [3, 10, 14, 40, 49], and two-dimensional Markov chains [4, 6, 19, 26, 65].

Recently, we developed a ring level random walk model to accurately represent the movement of a mobile terminal in two-dimensional cellular structures. This Markov chain model has been used (1) to analyze the paging area residence time and the cost of dynamic mobility management in a DBLMS [35]; (2) to study location distribution and reachability of a mobile terminal in a paging area, and to analyze the quality of service in a TBLMS [36]; (3) to investigate location distribution in a DBLMS and an MBLMS, and to study paging cost reduction methods [37].

Dynamic mobility management is an important and fundamental research issue in wireless communication, and significant effort has been devoted by many researchers. The performance of movement-based location management schemes has been investigated in [4, 10, 21, 31, 32, 33, 34, 38, 43, 61, 66]. The performance of distance-based location management schemes has been studied in [2, 8, 10, 14, 26, 35, 40, 41, 63, 67, 68]. The performance of time-based location management schemes has been considered in [3, 10, 11, 36, 44, 62]. Other studies were reported in [6, 13, 15, 18, 19, 20, 22, 45, 49, 58], and some comparative studies were in [12, 29, 30, 48, 50]. Dynamic location management in a wireless communication network with a finite number of cells has been treated as an optimization problem which is solved by using bio-inspired methods such as simulated annealing, neural networks, and genetic algorithms [7, 51, 53, 54, 55, 56]. The reader is also referred to the surveys in [5, 28, 52], [24] (Ch. 15), and [25] (Ch. 11).

Terminal paging methods with low cost and time delay have been studied by several researchers [1, 4, 9, 26, 27, 39, 46, 47, 57, 59, 60, 64]. Virtually all these studies focus on various selective paging methods. Two most important considerations for these methods are time delay and paging cost. A mobile terminal is located within certain geographical area divided into cells. At any moment, the mobile terminal resides in one of the cells. Each cell is associated with some probability that the mobile terminal is in the cell. A location distribution is a probability distribution of a mobile terminal in a geographical area. A selective paging method partitions the area into several disjoint regions, and proceeds in paging rounds when a phone call arrives. During each round, all cells in one region are polled by sending polling signals. The process is repeated until the mobile terminal is found, so that an incoming phone call can be routed to the mobile terminal. The number of paging rounds is the time delay, and the number of cells polled is the paging cost.

Minimizing both time delay and paging cost are conflicting requirements. A common strategy is to minimize paging cost with a time delay constraint. Given a location distribution over a search area and a time delay, the selective paging problem is to find a sequence of disjoint regions, such that the expected paging cost is minimized, subject to the constraint that the maximum or expected time delay does not exceed the given time limit [1, 9, 26, 27, 39, 46, 59, 60]. The most notable result is a dynamic programming algorithm [27, 39] to solve the problem in time proportional to the time delay and the number of cells [9]. However, all these studies suffer from a key issue which has not been well addressed, namely, location distribution of a mobile terminal in a paging area, although some effort was made for movement-based [4] and distance-based [26] location management schemes by using less accurate Markov chains. It is encouraging that significant progress in this direction has been made recently [36, 37], based on which the work in this chapter is developed.

3. The Models

3.1. Wireless Communication Networks

A wireless communication network has the common hexagonal cell configuration or mesh cell configuration. In the *hexagonal cell structure* (see Figure 1), cells are hexagons of identical size and each cell has six neighbors. In the *mesh cell structure* (see Figure 2), cells are squares of identical size and each cell

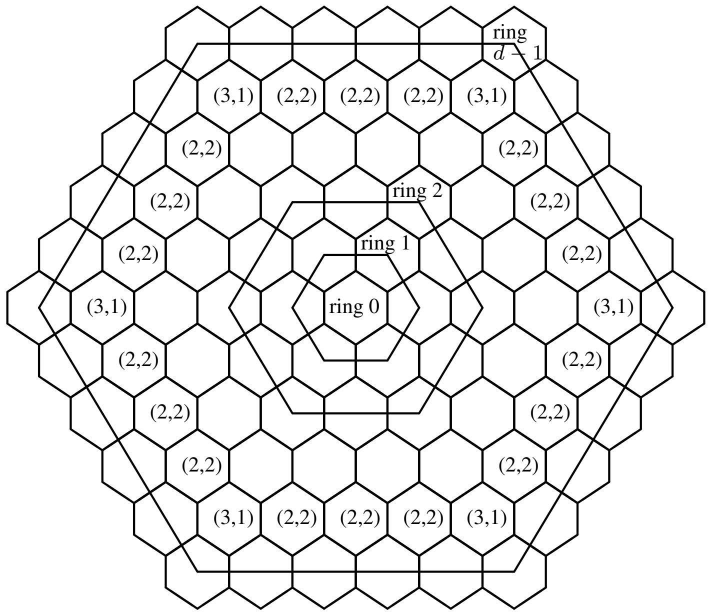

Figure 1. The hexagonal cell configuration. A cell s in ring r marked with (x, y) means that s has x neighbors in ring $r+1$ and y neighbors in ring $r-1$. Such values are useful in calculating the probabilities of moving into adjacent rings, i.e., the probability a_r of moving into ring $r+1$ and the probability b_r of moving into ring $r-1$.

has eight neighbors. Throughout the chapter, we let q be a constant such that $q = 3$ for the hexagonal cell configuration and $q = 4$ for the mesh cell configuration. By using the constant q, the hexagonal cell configuration and the mesh cell configuration can be treated in a unified way. For instance, we can say that each cell has $2q$ neighbors without mentioning the particular cell structure. The network is homogeneous in the sense that the behavior of a mobile terminal is statistically the same in all the cells.

Let s be the cell registered by a mobile terminal in the last location update. The cells in a wireless networks can be divided into rings, where s is the center of the network and called ring 0. The $2q$ neighbors of s constitute ring 1. In general, the neighbors of all the cells in ring r, except those neighbors in rings $r-1$ and r, constitute ring $r+1$. For all $r \geq 0$, the cells in ring r have distance r to s. For all $r \geq 1$, the number of cells in ring r is $2qr$. Notice that the rings

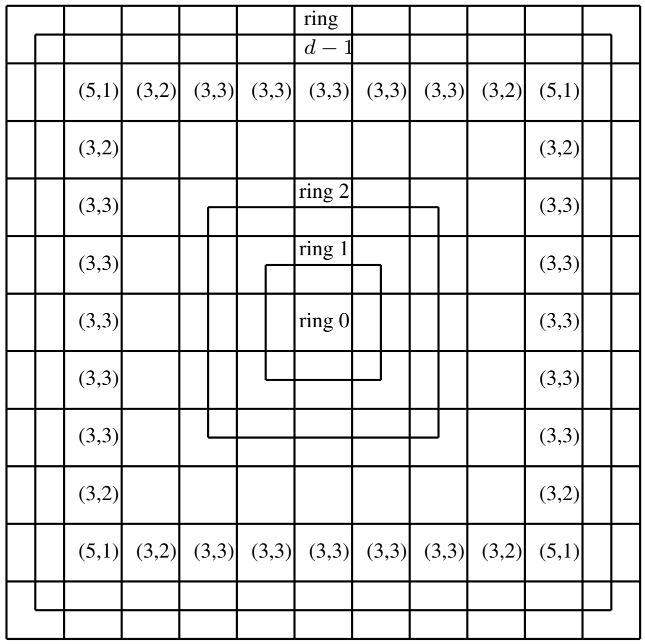

Figure 2. The mesh cell configuration. A cell s in ring r marked with (x, y) has the same meaning as that in Figure 1.

are defined with respect to s. When a mobile terminal updates its location to another cell s', s' becomes the center of the network, and ring r consists of the $2qr$ cells whose distance to s' is r.

When a mobile terminal u moves out of a cell s, it is normally assumed that u moves into one of s's $2q$ neighbors with equal probability [21, 31], although this assumption is irrelevant in analyzing location update cost of movement-based schemes [33]. However, how u moves into the neighboring cells is very important in (1) analyzing location update cost of distance-based schemes [35]; (2) analyzing location distribution, reachability, and quality of service of time-base schemes [36]; (3) analyzing location distribution in a paging area of a movement-based scheme or a distance-based scheme [37]; (4) and reducing paging cost of all schemes [37]. The reason is that the way u moves into the neighboring cells determines how fast or slow u reaches the boundary of a paging area.

3.2. Location Update Methods

A mobile terminal u constantly moves from cell to cell. Such movement also results in movement from ring to ring. Let the sequence of cells visited by u before the next phone call be denoted as s_0, s_1, s_2, ..., s_d, ..., where $s_0 = s$ is u's last registered cell (not the cell in which u received the previous phone call) and considered as u's current location.

There are three location update methods proposed in the current literature, namely, the distance-based method, the movement-based method, and the time-based method. In the *distance-based location update method*, location update is performed as soon as u moves into a cell s_j in ring d, where d is a distance threshold, i.e., the distance of u from the last registered cell s is d, such that s_j is registered as u's current location. It is clear that $j \geq d$, i.e., it takes at least d steps for u to reach ring d. In the *movement-based location update method*, location update is performed as soon as u has crossed cell boundaries for d times since the last location update, where d is a movement threshold. It is clear that the sequence of registered cells for u is $s_d, s_{2d}, s_{3d}, ...$. In the *time-based location update method*, location update is performed every τ units of time, where τ is a time threshold, regardless of the current location of u.

3.3. Terminal Paging Methods

In all dynamic location management schemes, a current *paging area* (PA) consists of rings $0, 1, 2, ..., d-1$, where d is some value appropriately chosen. We say that such a PA has radius d. Since the number of cells in ring r is $2qr$, for all $r \geq 1$, the total number of cells in a PA is $qd^2 - qd + 1$. It should be noticed that a PA is defined with respect to the current location of a mobile terminal, and is changed whenever a mobile terminal updates its location. The radius d of a PA can be adjusted in accordance with various cost and performance considerations. On the other hand, the location and size of a cell are fixed in a wireless network.

Two kinds of terminal paging methods have been proposed in the literature. In the *simple paging method*, the radius of a PA is fixed at d, where d is the distance threshold used by a distance-based location update method, or the movement threshold used by a movement-based location update method, or appropriately chosen in accordance with the time threshold used by a time-based location update method. In a *selective paging method*, cells in a PA or the entire wireless communication network are divided into disjoint regions, such that these regions are paged one after another successively, until a mobile terminal is found.

The simple paging method is the fastest method, since it sends polling signals only once. However, it is also the most expensive, since it sends polling signals to all cells in a paging area. On the other hand, a selective paging method trades cost with time, i.e., it covers a paging area gradually, with increased time delay but reduced paging cost.

3.4. Call Handling Models

We will consider two different call handling models.

In the *call plus location update* (CPLU) model, the location of a mobile terminal is updated each time a phone call arrives. That is, in addition to distance-based or movement-based or time-based location updates, the arrival of a phone call also initiates location update and defines a new PA. This causes the original location update cycle of a mobile terminal being interrupted. In the *call without location update* (CWLU) model, the arrival of a phone call has nothing to do with location update, that is, a mobile terminal still keeps its original location update cycles.

As seen from our previous studies [33, 34, 35, 36, 37], the analysis of the two different call handling models typically involve different types of renewal processes.

3.5. Notations

Throughout the chapter, we use $\boldsymbol{P}[E]$ to denote the probability of an event E. For a random variable T, we use $\boldsymbol{E}(T)$ to represent the expectation of T and $\lambda_T = \boldsymbol{E}(T)^{-1}$. The probability density function (pdf) of T is $f_T(t)$, and the cumulative distribution function (cdf) of T is $F_T(t)$.

There are several important random variables in the study of dynamic location management. The *inter-call time* T_c is defined as the length of the time interval between two consecutive phone calls. The *cell residence time* T_s is defined as the time a mobile terminal stays in a cell before it moves into a neighboring cell. The *paging area residence time* T_m is defined as the time a mobile terminal stays in the current PA before it moves out of the PA. The *location update time* T_u is defined as the time between two consecutive location updates, which is actually the time for a mobile terminal to across d cell boundaries in an

MBLMS, or the paging area residence time in a DBLMS, or the time threshold τ in a TBLMS. The quantity $\rho = \lambda_{T_c}/\lambda_{T_s}$ is the *call-to-mobility ratio*.

Dynamic location management is per-terminal based. A mobile terminal is specified by $f_{T_c}(t)$ and $f_{T_s}(t)$, where $f_{T_{c(t)}}$ is the call pattern and $f_{T_{s(t)}}$ is the mobility pattern.

The cost of dynamic location management contains two components, i.e., the cost of location update and the cost of terminal paging. The cost of location update is proportional to the number of location updates. If there are X_u location update between two consecutive phone calls, the cost of location update is $\Delta_u X_u$, where Δ_u is a constant. Since X_u is a random variable, the location update cost is actually calculated as $\Delta_u \boldsymbol{E}(X_u)$. The cost of terminal paging is proportional to the number of cells paged. For instance, if a PA has radius d, the cost of the simple paging method is $\Delta_p(qd^2 - qd + 1)$, where Δ_p is a constant. The cost of a selective paging method needs to be more carefully defined [37]. The cost of the aggressive paging method will be discussed in Section 5.

4. Location Distribution

Consider a mobile terminal u in a cell s. After staying in s for T_s amount of time, u moves out of s and enters into one of the $2q$ neighbors of s. It is clear that the movement of a mobile terminal can be described by a random walk among the cells. Such a random walk can be characterized by a two-dimensional Markov chain, where for each cell, we have a state in the Markov chain associated with the cell. The transition probability from a cell to a neighboring cell is $1/(2q)$. While the random walk among the cells and the cell level Markov chain accurately describe the movement of a mobile terminal in any cell structure, the number of states is exactly the same as the number of cells, which causes excessive computation cost in obtaining numerical data [35].

To reduce the number of states, we consider a random walk among the rings and construct a ring level Markov chain which contains states $K_0, K_1, K_2, ..., K_d, ...$, where state K_r means that a mobile terminal u is in ring r, $r \geq 0$. Initially, u is in state K_0. Instead of the probabilities of moving into neighboring cells, we are interested in the probabilities of moving into adjacent rings, i.e., the probability a_r of moving into ring $r+1$ and the probability b_r of moving into ring $r-1$. Let p_{ij} denote the transition probability from K_i to K_j, where $i, j \geq 0$. Then, we have $p_{01} = 1$, $p_{r,r+1} = a_r$, $p_{r,r-1} = b_r$, $p_{r,r} = 1 - a_r - b_r$, for all $r \geq 1$. All other p_{ij}'s not specified above are zeros. The exact values of the a_r's and the b_r's are extremely difficult to obtain. Fortunately, very accurate approximate values can be derived [35].

We use $p_{ij}^{(n)}$ to denote the n-step transition probability from K_i to K_j, where $i, j \geq 0$. The following result is well known ([23], p. 383), namely, if the nth power of $P = [p_{ij}]$ is $P^n = [g_{ij}]$, we have $p_{ij}^{(n)} = g_{ij}$, for all $i, j \geq 0$.

Let $N(d)$ denote the expected number of steps for a mobile terminal to move out of a paging area of radius d. $N(d)$ is actually the expected number of steps for a random walk starting from K_0 to reach K_d. It was shown in [35] that $N(d) \approx \alpha_q \cdot d(qd-1)/(q-1)$, where α_3 is roughly 0.55 and α_4 is roughly 0.60.

Let ξ_r, $r \geq 0$, denote the probability that a mobile terminal u is in ring r when a phone call arrives. The sequence $(\xi_0, \xi_1, \xi_2, ...)$ is called a *location distribution* of u. In this section, we analyze the location distribution of a mobile terminal in a paging area when a phone call arrives.

All theorems in this section are from [36, 37].

4.1. Movement-Based Schemes

4.1.1. The CPLU Model

In the CPLU model, there can be at most one phone call between two successive location updates, because each arriving phone call initiates a location update immediately. Consider any phone call C. Let X_s' denote the number of cell boundary crossings during the time interval of length T_c', i.e., the time between the moment of the last location update before C arrives (when the current PA is established) and the moment when C arrives.

The following theorem gives the location distribution of a mobile terminal in an MBLMS-CPLU.

Theorem 1. *In an MBLMS-CPLU, the probability that a mobile terminal is in ring r of a PA of radius d when a phone call arrives is*

$$\xi_r = \left(\sum_{j=0}^{d-1} \boldsymbol{P}[X_s' = j] \right)^{-1} \sum_{j=0}^{d-1} \boldsymbol{P}[X_s' = j] \frac{p_{0r}^{(j)}}{\sum_{r=0}^{d-1} p_{0r}^{(j)}},$$

for all $0 \leq r \leq d-1$, and any probability distributions of T_c and T_s.

If both T_c and T_s have exponential distributions with

$$f_{T_c}(t) = \lambda_c e^{-\lambda_c t},$$

and

$$f_{T_s}(t) = \lambda_s e^{-\lambda_s t},$$

we have

$$\boldsymbol{P}[X'_s = j] = \frac{\rho}{(\rho+1)^{j+1}},$$

for all $j \geq 0$, where $\rho = \lambda_c/\lambda_s$ is the *call-to-mobility ratio*. Hence, we get

$$\sum_{j=0}^{d-1} \boldsymbol{P}[X'_s = j] = \frac{1}{\rho}\left(1 - \frac{1}{(\rho+1)^d}\right).$$

The following theorem gives the location distribution of a mobile terminal in an MBLMS-CPLU in the special case when both T_c and T_s have exponential distributions.

Theorem 2. *If both T_c and T_s have exponential distributions, we have*

$$\xi_r = \frac{\rho(\rho+1)^d}{(\rho+1)^d - 1} \sum_{j=0}^{d-1} \frac{\rho}{(\rho+1)^{j+1}} \cdot \frac{p_{0r}^{(j)}}{\sum_{r=0}^{d-1} p_{0r}^{(j)}},$$

for all $0 \leq r \leq d-1$.

4.1.2. The CWLU Model

In the CWLU model, there can be many phone calls between two successive location updates. Let $C_1, C_2, ..., C_\gamma, ...$ be a sequence of phone calls between two successive ordinary location updates U and U'.

Let $T_{c,\gamma}$ be the inter-call time between $C_{\gamma-1}$ and C_γ, where $\gamma \geq 2$, and

$$T_c(\gamma) = T_{c,1} + T_{c,2} + \cdots + T_{c,\gamma}$$

denote the time between the moment of the last location update before C_γ arrives (when the current PA is established) and the moment when C_γ arrives, where $\gamma \geq 1$, and $T_{c,1} = T'_c$. Let $X_s(\gamma)$ denote the number of cell boundary crossings during the time interval of length $T_c(\gamma)$.

The following theorem gives the location distribution of a mobile terminal in an MBLMS-CWLU.

Theorem 3. *In an MBLMS-CWLU, the probability that a mobile terminal is in ring r of a PA of radius d when the γth phone call arrives is*

$$\xi_r = \left(\sum_{j=0}^{d-1} \boldsymbol{P}[X_s(\gamma) = j] \right)^{-1} \sum_{j=0}^{d-1} \boldsymbol{P}[X_s(\gamma) = j] \frac{p_{0r}^{(j)}}{\sum_{r=0}^{d-1} p_{0r}^{(j)}},$$

for all $0 \leq r \leq d-1$, and any probability distributions of T_c and T_s.

If both T_c and T_s have exponential distributions, we have

$$\begin{aligned} \boldsymbol{P}[X_s(\gamma) = j] &= \frac{\rho^\gamma}{(\rho+1)^{\gamma+j}} \cdot \frac{(j+1)(j+2)\cdots(j+\gamma-1)}{(\gamma-1)!} \\ &= \frac{\rho^\gamma}{(\rho+1)^{\gamma+j}} \binom{j+\gamma-1}{\gamma-1}, \end{aligned}$$

for all $j \geq 0$.

The following theorem gives the location distribution of a mobile terminal in an MBLMS-CWLU in the special case when both T_c and T_s have exponential distributions.

Theorem 4. *If both T_c and T_s have exponential distributions, we have*

$$\xi_r = \left(\sum_{j=0}^{d-1} \frac{\rho^\gamma}{(\rho+1)^{\gamma+j}} \binom{j+\gamma-1}{\gamma-1} \right)^{-1} \sum_{j=0}^{d-1} \frac{\rho^\gamma}{(\rho+1)^{\gamma+j}} \binom{j+\gamma-1}{\gamma-1} \frac{p_{0r}^{(j)}}{\sum_{r=0}^{d-1} p_{0r}^{(j)}},$$

for all $0 \leq r \leq d-1$. (When $\gamma = 1$, ξ_r is identical to that in Theorem 2.)

4.2. Distance-Based Schemes

4.2.1. The CPLU Model

The following theorem gives the location distribution of a mobile terminal in a DBLMS-CPLU.

Theorem 5. *In a DBLMS-CPLU, the probability that a mobile terminal is in ring r of a PA of radius d when a phone call arrives is*

$$\xi_r = \frac{\displaystyle\sum_{j=0}^{\infty} \boldsymbol{P}[X'_s = j] p_{0r}^{(j)}}{\displaystyle\sum_{j=0}^{\infty} \left(\sum_{r=0}^{d-1} p_{0r}^{(j)} \right) \boldsymbol{P}[X'_s = j]},$$

for all $0 \le r \le d-1$, and any probability distributions of T_c and T_s.

The following theorem gives the location distribution of a mobile terminal in a DBLMS-CPLU in the special case when both T_c and T_s have exponential distributions.

Theorem 6. *If both T_c and T_s have exponential distributions, we have*

$$\xi_r = \frac{\displaystyle\sum_{j=0}^{\infty} \frac{\rho}{(\rho+1)^{j+1}} p_{0r}^{(j)}}{\displaystyle\sum_{j=0}^{\infty} \left(\sum_{r=0}^{d-1} p_{0r}^{(j)} \right) \frac{\rho}{(\rho+1)^{j+1}}},$$

for all $0 \le r \le d-1$.

4.2.2. The CWLU Model

The following theorem gives the location distribution of a mobile terminal in a DBLMS-CWLU.

Theorem 7. *In a DBLMS-CWLU, the probability that a mobile terminal is in ring r of a PA of radius d when the γth phone call arrives is*

$$\xi_r = \frac{\displaystyle\sum_{j=0}^{\infty} \boldsymbol{P}[X_s(\gamma) = j] p_{0r}^{(j)}}{\displaystyle\sum_{j=0}^{\infty} \left(\left(\sum_{r=0}^{d-1} p_{0r}^{(j)} \right) \boldsymbol{P}[X_s(\gamma) = j] \right)},$$

for all $0 \le r \le d-1$, and any probability distributions of T_c and T_s.

The following result gives the location distribution of a mobile terminal in a DBLMS-CWLU in the special case when both T_c and T_s have exponential distributions.

Theorem 8. *If both T_c and T_s have exponential distributions, we have*

$$\xi_r = \frac{\displaystyle\sum_{j=0}^{\infty}\left(\frac{\rho^{\gamma}}{(\rho+1)^{\gamma+j}}\binom{j+\gamma-1}{\gamma-1}p_{0r}^{(j)}\right)}{\displaystyle\sum_{j=0}^{\infty}\left(\left(\sum_{r=0}^{d-1}p_{0r}^{(j)}\right)\frac{\rho^{\gamma}}{(\rho+1)^{\gamma+j}}\binom{j+\gamma-1}{\gamma-1}\right)},$$

for all $0 \le r \le d-1$. (When $\gamma = 1$, ξ_r is identical to that in Theorem 6.)

4.3. Time-Based Schemes

Let the pdf of an Erlang distribution be represented as

$$f_{\text{Erlang}}(\lambda,\gamma,t) = \frac{\lambda e^{-\lambda t}(\lambda t)^{\gamma-1}}{(\gamma-1)!},$$

and the cdf of an Erlang distribution be represented as

$$F_{\text{Erlang}}(\lambda,\gamma,t) = 1 - e^{-\lambda t}\sum_{j=0}^{\gamma-1}\frac{(\lambda t)^j}{j!}.$$

4.3.1. The CPLU Model

Let T_s' be the residual cell residence time of the cell where u resides when the last location update is performed.

The following theorem gives the location distribution of a mobile terminal in a TBLMS-CPLU.

Theorem 9. *In a TBLMS-CPLU, the probability that a mobile terminal is in ring r of a PA of radius d when a phone call arrives is*

$$\xi_r = \sum_{j=0}^{\infty}\boldsymbol{P}[X_s' = j]p_{0r}^{(j)},$$

for all $r \geq 0$*, where*

$$\boldsymbol{P}[X_s' = j] = \int_0^\infty \left(F_{T_s'+(j-1)T_s}(t) - F_{T_s'+jT_s}(t) \right) f_{T_c'}(t)dt,$$

for all $j \geq 0$*, and any probability distributions of* T_c *and* T_s*.*

If both T_c and T_s have exponential distributions, we have

$$\boldsymbol{P}[X_s' = j] = \frac{1}{F_{T_c}(\tau)} \cdot \frac{\rho}{(\rho+1)^{j+1}} \cdot F_{\text{Erlang}}(\lambda_s + \lambda_c, j+1, \tau),$$

for all $j \geq 0$.

The following result gives the location distribution of a mobile terminal in a TBLMS-CPLU in the special case when both T_c and T_s have exponential distributions.

Theorem 10. *If both* T_c *and* T_s *have exponential distributions, we have*

$$\xi_r = \sum_{j=0}^{\infty} \frac{\rho}{(\rho+1)^{j+1}} \cdot \frac{F_{\textit{Erlang}}(\lambda_s + \lambda_c, j+1, \tau)}{F_{T_c}(\tau)} \cdot p_{0r}^{(j)},$$

for all $r \geq 0$*.*

4.3.2. The CWLU Model

The following theorem gives the location distribution of a mobile terminal in a TBLMS-CWLU.

Theorem 11. *In a TBLMS-CWLU, the probability that a mobile terminal is in ring* r *of a PA of radius* d *when the* γ*th phone call arrives is*

$$\xi_r = \sum_{j=0}^{\infty} \boldsymbol{P}[X_s(\gamma) = j] p_{0r}^{(j)},$$

for all $r \geq 0$ *and* $\gamma \geq 1$*, where*

$$\boldsymbol{P}[X_s(\gamma) = j] = \int_0^\infty \left(F_{T_s'+(j-1)T_s}(t) - F_{T_s'+jT_s}(t) \right) f_{T_c(\gamma)}(t)dt,$$

for all $j \geq 0$*, and any probability distributions of* T_c *and* T_s*.*

The following result gives the location distribution of a mobile terminal in a TBLMS-CWLU in the special case when both T_c and T_s have exponential distributions.

Theorem 12. *If both T_c and T_s have exponential distributions, we have*

$$\xi_r = \sum_{j=0}^{\infty} \binom{j+\gamma-1}{j} \frac{\rho^\gamma}{(\rho+1)^{j+\gamma}} \cdot \frac{F_{Erlang}(\lambda_s+\lambda_c, j+\gamma, \tau)}{F_{Erlang}(\lambda_c, \gamma, \tau)} \cdot p_{0r}^{(j)},$$

for all $r \geq 0$ and $\gamma \geq 1$. (When $\gamma = 1$, ξ_r is identical to that in Theorem 10.)

5. Aggressive Paging

The *aggressive paging* method realizes paging cost reduction with high QoS. The way to reduce the paging cost is simply to page rings $0, 1, 2, ..., d' - 1$, where $d' < d$. The paging cost is $\Delta_p(qd'^2 - qd' + 1)$.

However, it is not guaranteed that a mobile terminal can be found in the reduced PA. Thus, QoS becomes an important issue for the aggressive paging method. By using the ξ_r's, the probability of finding a mobile terminal in the reduced PA of radius d' when a phone call arrives can be obtained easily. The following theorem gives the probability that a mobile terminal can be reached, i.e., it is in the reduced PA, when the next phone call arrives.

Theorem 13. *In an MBLMS-CPLU or a DBLMS-CPLU or a TBLMS-CPLU, the probability $I(d')$ that a mobile terminal is in the reduced PA of radius d' when a phone call arrives is*

$$I(d') = \sum_{r=0}^{d'-1} \xi_r,$$

for all $d' \geq 1$.

The aggressive paging method is acceptable to a mobile terminal u if the probability $I(d')$ that u is found in the reduced PA when a phone call arrives is above certain level Q. We define $I(d')$ as a measure of QoS.

Our discussion in this chapter can be summarized as follows.

Theorem 14. *The aggressive paging method has one round of paging, cost of paging $\Delta_p(qd'^2 - qd' + 1)$, and QoS $I(d')$, where d' is the smallest value such that $I(d') \geq Q$.*

6. Performance Data

In this section, we demonstrate numerical data to show paging cost reduction obtained by the aggressive paging method for a given QoS. We consider an exponential distribution of T_c with

$$f_{T_c}(t) = \lambda_c e^{-\lambda_c t},$$

and an exponential distribution of T_s with

$$f_{T_s}(t) = \lambda_s e^{-\lambda_s t}.$$

It is clear that $\rho = \lambda_c/\lambda_s$. The parameters are set as $\lambda_c = 1$, $\lambda_s = 10$, $\rho = 0.1$, $\Delta_p = 1$, and $\Delta_u = 100$. All our data are based on the location distribution when a phone call in CPLU or the first phone call in CWLU arrives.

In Figures 3–4, we consider MBLMS for $q = 3$ and $q = 4$ respectively. For both CPLU and CWLU call handling methods, we display the total cost of location management for $Q = 0.990, 0.999, 1.000$. Notice that when $Q = 1.000$, the aggressive paging method becomes the simple paging method. It is easily observed that slight reduction of Q results in significant reduction of paging cost, especially when d is large.

In Figures 5–6, we consider DBLMS for $q = 3$ and $q = 4$ respectively. For both CPLU and CWLU call handling methods, we display the total cost of location management for $Q = 0.990, 0.999, 1.000$. Is it easily observed that slight reduction of Q results in noticeable reduction of paging cost, especially when d is large. However, the reduction is not as significant as MBLMS, because a mobile terminal can be further away from the center of a PA in a DBLMS than in an MBLMS. This results in increased value of d' to cover the mobile terminal for a specified Q.

In Figures 7–8, we consider TBLMS with $\tau = d\boldsymbol{E}(T_s)$ (to simulate MBLMS) for $q = 3$ and $q = 4$ respectively. For both CPLU and CWLU call handling methods, we display the total cost of location management for $Q = 0.9900, 0.9990, 0.9999$. Notice that Q cannot be 1.0000 in TBLMS, since it can never be guaranteed that a mobile terminal can be found in one round of paging. It is easily observed that the paging cost is very low even for very high Q.

In Figures 9–10, we consider TBLMS with $\tau = N(d)\boldsymbol{E}(T_s)$ (to simulate DBLMS) for $q = 3$ and $q = 4$ respectively. For both CPLU and CWLU call handling methods, we display the total cost of location management for $Q = 0.9900, 0.9990, 0.9999$. It is clear that the paging cost is higher than that in Figures 7–8 due to increased τ, which results in increased value of d' to cover the mobile terminal for a specified Q. However, the paging cost is still very low even for very high Q.

7. Performance Comparison

Let $M_{\text{CPLU}}(d)$, $M_{\text{CWLU}}(d)$, $D_{\text{CPLU}}(d)$, $D_{\text{CWLU}}(d)$, $T_{\text{CPLU}}(\tau)$, and $T_{\text{CWLU}}(\tau)$ be the location update cost of an MBLMS with CPLU, an MBLMS with CWLU, a DBLMS with CPLU, a DBLMS with CWLU, a TBLMS with CPLU, and a TBLMS with CWLU respectively.

Let $\phi_{ij}^{(n)}$ be the probability that in a random walk starting from state K_i, the first entry to state K_j occurs at the nth step, where $n \geq 1$. In particular, $(\phi_{0d}^{(d)}, \phi_{0d}^{(d+1)}, ..., \phi_{0d}^{(n)}, ...)$ is called the *first-passage distribution* for K_d.

By Theorems 6 and 11 in [33], Theorems 11 and 12 in [35], and Theorems 14 and 15 in [36], we know the following results.

- $M_{\text{CPLU}}(d) = \Delta_u \left(\dfrac{(\rho+1)^d}{(\rho+1)^d - 1} \right)$.
- $M_{\text{CWLU}}(d) = \dfrac{\Delta_u}{\rho d}$.
- $D_{\text{CPLU}}(d) = \Delta_u \left(1 - \displaystyle\sum_{n=d}^{\infty} \dfrac{\phi_{0d}^{(n)}}{(\rho+1)^n} \right)^{-1}$.
- $D_{\text{CWLU}}(d) = \dfrac{\Delta_u}{\rho N(d)}$.
- $T_{\text{CPLU}}(d\boldsymbol{E}(T_s)) = \dfrac{\Delta_u}{1 - e^{-\rho d}}$.
- $T_{\text{CWLU}}(d\boldsymbol{E}(T_s)) = \dfrac{\Delta_u}{\rho d}$.
- $T_{\text{CPLU}}(N(d)\boldsymbol{E}(T_s)) = \dfrac{\Delta_u}{1 - e^{-\rho N(d)}}$.

- $T_{\text{CWLU}}(N(d)\boldsymbol{E}(T_s)) = \dfrac{\Delta_u}{\rho N(d)}$.

The following theorem compares the location update costs of the location update methods.

Theorem 15. *We have the following relations:*

$$\begin{array}{l} D_{CPLU}(d) < M_{CPLU}(d), \quad d > 1; \\ D_{CWLU}(d) < M_{CWLU}(d), \quad d > 1; \\ T_{CPLU}(d\boldsymbol{E}(T_s)) < M_{CPLU}(d); \\ T_{CWLU}(d\boldsymbol{E}(T_s)) = M_{CWLU}(d); \\ T_{CPLU}(N(d)\boldsymbol{E}(T_s)) < D_{CPLU}(d); \\ T_{CWLU}(N(d)\boldsymbol{E}(T_s)) = D_{CWLU}(d). \end{array}$$

Proof. The first inequality states that a DBLMS-CPLU has lower location update cost than an MBLMS-CPLU for all $d > 1$. This can be seen by noticing that

$$\begin{aligned} 1 - \sum_{n=d}^{\infty} \frac{\phi_{0d}^{(n)}}{(\rho+1)^n} &= 1 - \frac{1}{(\rho+1)^d} \sum_{n=d}^{\infty} \frac{\phi_{0d}^{(n)}}{(\rho+1)^{n-d}} \\ &> 1 - \frac{1}{(\rho+1)^d} \sum_{n=d}^{\infty} \phi_{0d}^{(n)} \\ &= \frac{(\rho+1)^d - 1}{(\rho+1)^d}. \end{aligned}$$

Notice that when $d = 1$, we have $\phi_{0d}^{(1)} = 1$ and $\phi_{0d}^{(n)} = 0$ for all $n > 1$. Therefore, we get $D_{\text{CPLU}}(d) = M_{\text{CPLU}}(d) = (\rho+1)/\rho$.

The second inequality states that a DBLMS-CWLU has lower location update cost than an MBLMS-CWLU for all $d > 1$. This is obvious since $N(d) > d$ for all $d > 1$. Notice that when $d = 1$, we have $N(d) = d$.

The third inequality states that a TBLMS-CPLU with $\tau = d\boldsymbol{E}(T_s)$ (to simulate MBLMS) has lower location update cost than an MBLMS-CPLU. The inequality

$$\frac{1}{1 - e^{-\rho d}} < \frac{(\rho+1)^d}{(\rho+1)^d - 1}$$

is identical to

$$\frac{e^{\rho d}}{e^{\rho d}-1} < \frac{(\rho+1)^d}{(\rho+1)^d-1},$$

that is, $e^{\rho d} > (\rho+1)^d$, which follows the fact that $e^{\rho} > \rho+1$ for all $\rho > 0$.

The fourth relation states that a TBLMS-CWLU with $\tau = d\boldsymbol{E}(T_s)$ has the same location update cost as an MBLMS-CWLU. This is easy to observe.

The fifth inequality states that a TBLMS-CPLU with $\tau = N(d)\boldsymbol{E}(T_s)$ (to simulate DBLMS) has lower location update cost than a DBLMS-CPLU. The inequality

$$\frac{1}{1-e^{-\rho N(d)}} < \left(1 - \sum_{n=d}^{\infty} \frac{\phi_{0d}^{(n)}}{(\rho+1)^n}\right)^{-1},$$

is equivalent to

$$\frac{1}{e^{\rho N(d)}} < \sum_{n=d}^{\infty} \frac{\phi_{0d}^{(n)}}{(\rho+1)^n}.$$

Since $e^{\rho} > \rho+1$ for all $\rho > 0$, it suffices to show that

$$\frac{1}{(\rho+1)^{N(d)}} \le \sum_{n=d}^{\infty} \frac{\phi_{0d}^{(n)}}{(\rho+1)^n}.$$

Consider the function

$$f(X) = \frac{1}{(\rho+1)^X},$$

where X is a random variable with $\boldsymbol{P}[X=n] = \phi_{0d}^{(n)}$ for all $n \ge d$. The left hand side of the last inequality is $f(\boldsymbol{E}(X))$ and the right hand side of the last inequality is $\boldsymbol{E}(f(X))$. This is exactly a Jensen's inequality, i.e.,

$$f(\boldsymbol{E}(X)) \le \boldsymbol{E}(f(X)),$$

if $f(x)$ is a convex cup function ([69], p. 579).

The last relation states that a TBLMS-CWLU with $\tau = N(d)\boldsymbol{E}(T_s)$ has the same location update cost as a DBLMS-CWLU. This is easy to observe.

This proves the theorem. ∎

Theorem 15 only compares the location update costs. It is more interesting and important to compare the total cost of location management (i.e., location update cost plus terminal paging cost) with the same paging speed (i.e., one round of paging) and paging quality (i.e., Q) for various location management schemes. While the relationship among location update costs are clearly given by Theorem 15, the relationship among terminal paging costs are subtle. It is clear that since different location management schemes have different location distributions, different location management schemes have different values of d' to ensure $I(d') \geq Q$ for the same Q, and thus have different terminal paging costs.

Figures 3 and 5 reveal that for $q = 3$ and $Q = 0.99$, MBLMS-CPLU has higher (lower, respectively) total location management cost than DBLMS-CPLU for $d \leq 8$ ($d \geq 9$, respectively). When d is small, the total cost is higher due to shorter location update time and higher location update cost. When d is large, the total cost is lower due to smaller value of d' (i.e., a mobile terminal is more likely to be closer to the center of a PA) and lower terminal paging cost. Similar result also holds for $Q = 0.999$, CWLU, and $q = 4$ (see Figures 4 and 6).

Figures 3–4 and 7–8 reveal that for the same Q, the total location management cost of TBLMS with $\tau = d\boldsymbol{E}(T_s)$ is lower than or the same as that of MBLMS, except for some small values of d.

Figures 5 and 9 reveal that when $q = 3$, for $Q = 0.99$, the total location management cost of TBLMS-CPLU with $\tau = N(d)\boldsymbol{E}(T_s)$ is lower (higher, respectively) than or the same as that of DBLMS-CPLU when $d \geq 11$ ($d \leq 10$, respectively). However, for $Q = 0.999$, the total location management cost of TBLMS-CPLU with $\tau = N(d)\boldsymbol{E}(T_s)$ is higher than that of DBLMS-CPLU, except for some large values of d. Similar result also holds for CWLU and $q = 4$ (see Figures 6 and 10).

8. Conclusion

We have proposed the aggressive paging method, which is able to achieve the fastest speed, low cost, and high QoS simultaneously. Our numerical data confirm the effectiveness and efficiency of the aggressive paging method. Such a result has never been discovered in the existing literature.

Figure 3. Location Management Cost in MBLMS with Aggressive Paging ($q = 3$).

Figure 4. Location Management Cost in MBLMS with Aggressive Paging ($q = 4$).

Figure 5. Location Management Cost in DBLMS with Aggressive Paging ($q = 3$).

Figure 6. Location Management Cost in DBLMS with Aggressive Paging ($q = 4$).

Figure 7. Location Management Cost in TBLMS with Aggressive Paging ($\tau = d\boldsymbol{E}(T_s)$, $q = 3$).

Figure 8. Location Management Cost in TBLMS with Aggressive Paging ($\tau = d\boldsymbol{E}(T_s)$, $q = 4$).

Figure 9. Location Management Cost in TBLMS with Aggressive Paging ($\tau = N(d)\boldsymbol{E}(T_s)$, $q = 3$).

Figure 10. Location Management Cost in TBLMS with Aggressive Paging ($\tau = N(d)\boldsymbol{E}(T_s)$, $q = 4$).

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