Analysis of Dynamic Location Management for PCS Networks

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***Abstract*—Location management is a key issue in personal communication service (PCS) networks. Performance analysis plays important roles in the implementation of location management methods and system design in PCS networks. Existing PCS networks have the home location registers (HLRs) and visitor location registers (VLRs) architecture for location management. Some interesting dynamic location management methods are proposed to improve the system performance of PCS networks. However, the existing performance analysis of the dynamic location management methods are too simple and not available for PCS networks with real HLR/VLR architecture. One of the reasons is the complexity and difficulty of the problem. In this paper, we challenge the problem and successfully establish a new analytical model available for the analysis of the important dynamic movement-based location management method for PCS networks.**

***Index Terms*—Location management, performance analysis, personal communication service (PCS) networks.**

I. INTRODUCTION

PERSONAL communication service (PCS) networks [6], [8], [10] are mobile communication systems that enable mobile terminals to economically transfer any form of information between any desired locations at any time. In a PCS network, a given geographically serviced area is divided into cells. In each cell, there is a base station which is used to communicate with mobile terminals over preassigned radio frequencies. Groups of several cells are connected to a mobile switching center (MSC) through which the calls are then routed to the telephone networks. MSC is a telephone exchange specially assembled for mobile applications. It interfaces between the mobile phones (via base stations) and the public switched telephone network (PSTN) or public switched data network (PSDN), which makes the mobile services widely accessible to the public.

Location management, which keeps track of the mobile terminals moving from place to place in PCS networks, is a key issue in PCS networks [3], [5], [10], [12], [19], [23]. The mobile terminals are the subscribers that use either the automobile hand held telephones or portable computers to send and receive calls.

The location management system resides in MSCs. It contains two databases to facilitate the tracking of mobile terminals: the home location register (HLR) and the visitor location register (VLR). The HLR contains the permanent data (e.g., directory number, profile information, current location, and validation period) of the mobile terminals whose primary subscription is within the area. For each mobile terminal, it contains a pointer to the VLR to assist routing incoming calls. The VLR is associated with an MSC in the networks. It contains a temporary record for all mobile terminals currently active within the service area of the MSC. The VLR retrieve information for handling calls to or from a visiting mobile terminal. To facilitate the tracking of a moving mobile terminal, a PCS network is partitioned into many location areas (LAs). Each LA includes tens or hundreds of cells and is serviced by a VLR. The HLR/VLR architecture allows the system to page a mobile terminal within a subset of the system called a paging area (PA), whose size is less than or equal to that of an LA. All the popular existing PCS networks such as Pan-European Digital Celluar (GSM) [9] and North American Digital Celluar (IS-54) [21] employ the HLR/VLR architecture [15].

There are two basic operations in location management: *location update* and *paging*. Location update is the process through which system tracks the location of mobile terminals that are not in conversations. The mobile terminal reports its up-to-date location information dynamically. A PA may include one or more cells. When an incoming call arrives, the system searches for the mobile terminal by sending polling signals to cells in the PA. This searching process is referred to as paging. To perform location update or paging will incur a significant amount of cost (e.g., wireless bandwidth and processing power at the mobile terminals, the base stations, and databases), which should be minimized in the systems.

In the existing PCS networks, the size of a PA is fixed and is equal to the LA. Each cell in the LA will page once when a call arrives for a mobile terminal currently registered in the LA. This is the static location update and paging scheme in the sense that the PA is determined *a priori*. Under the static schemes, however, a mobile terminal close to the boundary of an LA may perform excessive location updates as it moves back and forth between two LAs.

Dynamic location management methods are proposed for dealing with the problems of static schemes. In dynamic schemes, the size of a LA is determined dynamically according to the changes of mobility and calling patterns of mobile terminals. Three kinds of dynamic location management schemes have been proposed [4], namely, distance based, movement based, and time based. Under the distance-based scheme, the

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location update is performed whenever the distance (in term of number of cells) between the current cell of the terminal and the last cell in which the update is performed is d, where d is the distance threshold. Under the movement-based scheme, the location update is performed whenever the mobile terminal completes d movements between cells, where d is the movement threshold. Under the time-based scheme, the location update is performed every t units of time, where t is the time threshold. It has been pointed out that the movement-based location update method may be the most practical, because it is effective and can be easily implemented under the framework of current PCS networks [3].

To implement the dynamic location update scheme in a real PCS network, we had to consider the real network architectures with HLR/VLR databases. Otherwise, we have to change all the network architecture a lot, which will be not a practical approach. However, the existing performance analyses [1]–[4], [18] are too simple and are not available for the dynamic location management with real HLR/VLR architecture. One of the reasons is the complexity and difficulty of the problem. To exploit and implement these dynamic location management methods in real PCS networks with HLR/VLR architecture, it is highly desirable to have the performance analysis for system design and implementation.

In this paper, we challenge the problem of the performance analysis of the dynamic movement-based location management method for PCS networks with the HLR/ VLR architectures. To evaluate the performance of the dynamic location management with HLR/VLR architectures, it is necessary to consider the movement among both PAs and LAs carefully. Furthermore, in the dynamic location update schemes, the size of a PA is changed while the size of an LA is fixed. This makes the analysis much more difficult. Despite the complexity of the problem, a novel analytic model is successfully established. The proposed analytical model enables us to formulate the HLR location update costs, the VLR location update costs, and the costs of paging with the system parameters, which capture the mobility and the incoming call arrival patterns of each mobile terminal in detail.

By using the proposed model, we present the performance evaluation and comparison of the movement-based location update scheme and existing static location update scheme under various parameters and mobility and calling patterns: the HLR and VLR location update costs, polling cost, the mean cell residence time, the mean LA residence time, the mean time interval between two consecutive phone calls to a mobile terminal, etc. These studies show clearly the performance improvement of the movement-based location update scheme over the existing static scheme. These studies are useful in the system design and implementation. They also provide insights into the structure of the optimal movement-based location update scheme.

The rest of this paper is organized as follows. System description is presented in Section II. Sections III and IV establish an analytic model to formulate the costs of location update and paging in the dynamic location update scheme and the static location update scheme for PCS networks under the framework of existing network architectures with HLR and VLR databases. The performance evaluation and comparison of the movement-based location update scheme and existing static location update scheme are studied in Section V. Section VI concludes this paper.

II. SYSTEM DESCRIPTION

Consider a PCS network which coverage area is divided into LAs, each of which consists of tens or hundreds of cells and is serviced by a VLR. A mobile terminal resides in a cell it visits for a random time interval and moves on to the next cell.

The movement-based location update scheme and the existing static location update scheme are considered in this paper. The location update involves the update of location data in both HLR and VLR databases. In the movement-based location update scheme, a mobile terminal registers at a new VLR and its new location is reported to HLR when it moves across d cells since the last location update, where d is a threshold value. In the static location update scheme, a mobile terminal registers at the new VLR when it moves to a new LA. The action is referred to as the *registration operation*. For the case that a mobile terminal moves to a different LA, it will be followed by a deregistration operation to remove the obsolete record in the old VLR. In IS-54, HLR sends a deregistration message to the old VLR. For convenience, a location data update in HLR is referred to as a *HLR location update* and a set of registration and deregistration operations in VLRs is referred to as a *VLR location update*.

For the movement-based location update method, we define the *center cell* to be the cell where the last VLR location registration occurred. As soon as a call for a mobile terminal arrives, the network initiates the terminal paging process to locate the called mobile terminal. The PA is the covering area within a distance $d-1$ from the center cell. For the system with the static location update scheme, the PA is the same as an LA.

We consider the PCS network with common hexagonal cell configurations shown in Fig. 1. For the hexagonal cell configuration, cells are hexagonal shaped and each cell has six neighbors. There are many rings of cells in the hexagonal cell configuration. The innermost ring (i.e., ring “0”) consists of only the center cell in the movement-based location update scheme. Ring “0” is surrounded by ring “1”, which in turn is surrounded by ring “2” and so on. We note that in a real PCS network, the cells may have different shapes and sizes. The rings associated with a given center may have irregular shapes. For demonstration purpose, we assume that homogeneous cells are used. The *distance* from the center to a cell is measured in terms of the number of rings from the center cell to the cell. The number of cells in ring i, denoted by $g(i)$, is given as follows:

$$\begin{aligned}&g(0)=1\\&g(i)=6i, \quad \text{for hexagonal configuration} \quad i=1,2,3,\cdots.\end{aligned}$$

The size of each cell is determined based on the number of mobile channels available per cell and the channel allocation scheme used. The location tracking mechanism can be applied to both the macrocell environment, where cell radius is in terms of several kilometers and microcell environment, where cell radius is in terms of hundreds of meters. In this paper, the size and

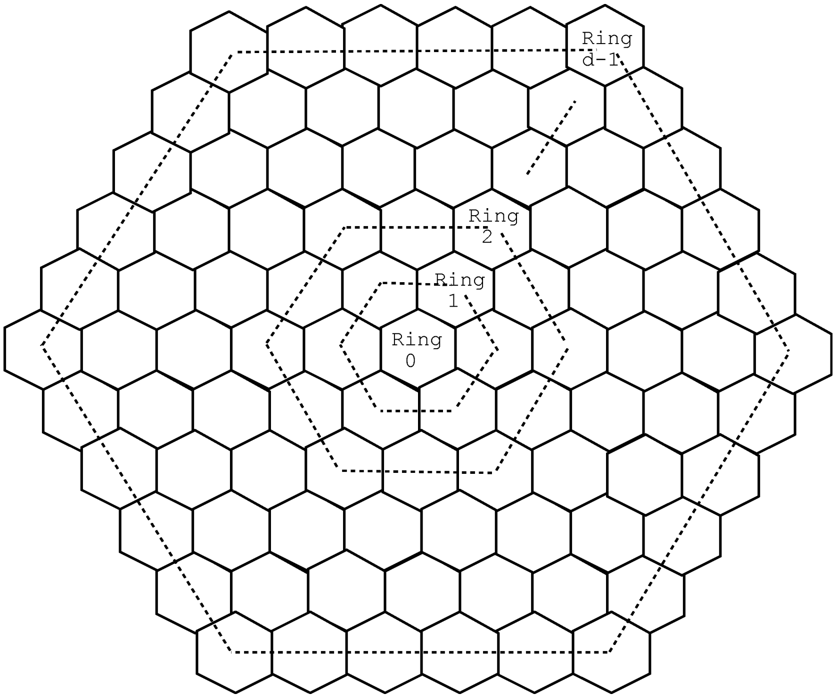

Fig. 1. The hexagonal configuration.

shape of a cell are indirectly reflected by the cell residence time value. If the size of cells is small, the mean residence time will be relatively small and vice versa.

In the existing cellular phone systems, all cells in the PA (or LA) are paged each time when an incoming call arrives [8], [12]. Here, we use the existing paging scheme.

III. THE ANALYTICAL MODEL

To establish the analytical model for the dynamic movement-based location management with HLR/VLR architectures, it is necessary to consider the movement among both PAs and LAs carefully. Furthermore, in the dynamic location management, the size of PA is changed while the size of LA is fixed, which makes the analysis difficult to be conducted. We challenge the problem and develop the new model successfully.

In this section, we first provide a general formulation of the total expected cost function of the dynamic location management. Then, we present the detailed derivation of each cost function.

In the dynamic movement-based location management with HLR/VLR architecture, there are costs for location update and paging. Furthermore, in the HLR/VLR network architectures, there are two kinds of location updates: HLR location updates that update the location data in HLRs and VLR location updates that update the location data in VLRs. Denote the expected costs per call arrival of HLR location updates, VLR location updates, and the paging by $C_{\mathrm{hlr}}, C_{\mathrm{vlr}}$, and C_p, respectively. The total costs of location update and paging per call arrival is the sum of HLR and VLR location updates and the cost of paging

$$\mathrm{TC}_{\mathrm{mb}} = C_{\mathrm{hlr}} + C_{\mathrm{vlr}} + C_p. \tag{1}$$

In the following, we derive the expected costs for HLR and VLR location updates (C_{hlr} and C_{vlr}) and cost for paging (C_p) for the dynamic movement-based location management with HLR/VLR architecture one by one in detail.

A. Cost of HLR Location Updates

Let the cost for performing a HLR location update be δ_{hlr}, which accounts for the wireless and wireline bandwidth utilization and the computational cost for processing a location update in HLR. Let n_{hlr} be the average number of HLR location updates between two call arrivals. Then, the expected cost of HLR location updates is expressed as

$$C_{\mathrm{hlr}} = \delta_{\mathrm{hlr}} \cdot n_{\mathrm{hlr}}. \tag{2}$$

The average number of HLR location updates between two call arrivals n_{hlr} should be calculated carefully. Let $\alpha(K)$ denote the probability that there are K LA boundary crossings between two call arrivals. n_{hlr} is the same as the average number of LA boundary crossings between two call arrivals, which is given by

$$n_{\mathrm{hlr}} = \sum_{K=1}^{\infty} K\alpha(K). \tag{3}$$

The Poisson process and exponential process are good models used to describe the arrivals of incoming phone calls and the service time of a phone call, respectively (e.g., [3], [17]). In the analysis, we assume that the residence time of a mobile terminal in an LA is an exponential distributed random variable with rate λ_m and the call arrival to each mobile terminal is a Poisson process with rate λ_c. With these parameters, we derive the probability $\alpha(K)$ in a similar way, as shown in [20], as follows:

$$\alpha(K) = \frac{\lambda_c}{\lambda_m + \lambda_c}\left(\frac{\lambda_m}{\lambda_m + \lambda_c}\right)^K, \qquad K = 0, 1, 2, \ldots. \tag{4}$$

For the sake of convenience, let

$$\rho_{mc} = \frac{\lambda_m}{\lambda_m + \lambda_c}. \tag{5}$$

Then we have

$$\alpha(K) = (1 - \rho_{mc})\rho_{mc}^K. \tag{6}$$

Substituting (6) into (3), n_{hlr} is calculated as follows:

$$\begin{aligned} n_{\mathrm{hlr}} &= \sum_{K=1}^{\infty} K\alpha(K) \\ &= \sum_{K=1}^{\infty} K(1-\rho_{mc})\rho_{mc}^K \\ &= (1-\rho_{mc})\rho_{mc}\left(\sum_{K=1}^{\infty}\rho_{mc}^K\right)' \\ &= (1-\rho_{mc})\rho_{mc}\left(\frac{\rho_{mc}}{1-\rho_{mc}}\right)' \\ &= (1-\rho_{mc})\rho_{mc}\frac{1}{(1-\rho_{mc})^2} \\ &= \frac{\lambda_m}{\lambda_c}. \end{aligned} \tag{7}$$

Substituting (7) into (2), we obtain the following simple and clear form of the cost function of location update in database HLR:

$$C_{\mathrm{hlr}} = \delta_{\mathrm{hlr}} \cdot \frac{\lambda_m}{\lambda_c}. \tag{8}$$

B. Cost of VLR Location Updates

The part of deriving the cost of VLR location updates is the most difficult one in the analysis. We have to take the movement of mobile terminals among both PAs and LAs into account. Note that the size of an LA is fixed while a PA is variable. First, we give a general formulation of the cost of VLR location updates. Then, we derive the average number of location updates in VLRs by considering the movement among both PAs and LAs.

Denote the cost for performing a VLR location update by δ_{vlr}, which accounts for the wireless and wireline bandwidth utilization and the computational requirements in order to process a location updates in VLR. Let n_{vlr} be the average number of VLR location updates per call arrival. Then the cost of VLR location updates is

$$C_{\mathrm{vlr}} = \delta_{\mathrm{vlr}} \cdot n_{\mathrm{vlr}}. \tag{9}$$

Without loss of generality, suppose that the mobile terminal resides in the LA LA_0 when the previous phone call arrived. The average number of location updates in VLRs per call arrival is expressed as follows:

$$n_{\mathrm{vlr}} = \sum_{K=0}^{\infty} n_{\mathrm{vlr},K} \cdot \alpha(K) \tag{10}$$

where $n_{\mathrm{vlr},K}$ is the average number of location updates in VLRs with movement-based location update scheme when mobile terminal p receives the next phone call in the Kth LA LA_K $(K = 0, 1, 2, \ldots)$.

In order to calculate the value of $n_{\mathrm{vlr},K}$, it is necessary to obtain the following four probabilities that can describe the movements of a mobile terminal among both PAs and LAs. Note that the size of a PA is changed according to the threshold d, while the size of an LA is fixed.

1) $\varepsilon_1(k)$: The probability that there are k cell boundary crossings within LA_0, where the previous phone call arrived when mobile terminal p receives the next phone call in the same LA. In this case, $K = 0$, i.e., there is no LA boundary crossing.
2) $\varepsilon_2(k)$: The probability that there are k cell boundary crossings within LA_0 when mobile terminal p enters LA_1. In this case, $K > 0$, i.e., there are LA boundary crossings.
3) $\varepsilon_3(k)$: The probability that there are k cell boundary crossings within LA_i during period $t_{M_i}(1 \le i \le K-1, K > 0)$.
4) $\varepsilon_4(k)$: The probability that there are k cell boundary crossings after entering the last $\mathrm{LA}_K(K > 0)$ until the next phone call arrival.

Note that the location updates in VLR occur when the mobile terminal crosses d cell boundaries or the boundary of an LA with the movement-based method. With the probabilities of $\varepsilon_1(k), \varepsilon_2(k), \varepsilon_3(k)$ and $\varepsilon_4(k)$, the average number of location updates in VLRs $n_{\mathrm{vlr},K}$ can be expressed as follows:

$$n_{\mathrm{vlr},K} = \begin{cases} \sum\limits_{l=1}^{\infty} l \sum\limits_{j=ld}^{(l+1)d-1} \varepsilon_1(j), & \text{for } K = 0 \\ \sum\limits_{l=1}^{\infty} l \sum\limits_{j=ld}^{(l+1)d-1} \varepsilon_2(j) & \\ +(K-1)\sum\limits_{l=1}^{\infty} l \sum_{j=ld}^{(l+1)d-1} \varepsilon_3(j) & \\ +\sum\limits_{l=1}^{\infty} l \sum_{j=ld}^{(l+1)d-1} \varepsilon_4(j), & \text{for } K \ge 1. \end{cases} \tag{11}$$

In (11), $K = 0$ means that there is no LA boundary crossing and $K \ge 0$ means that there are $K(K \ge 0)$ LA boundary crossings. We proceed to the calculation of these four probabilities.

1) Calculation of $\varepsilon_1(k), \varepsilon_2(k), \varepsilon_3(k)$ *and* $\varepsilon_4(k)$*:* Assume that residence time of a mobile terminal in a cell is an exponential distributed time interval with rate λ_s. For convenience, we use the timing diagrams shown in Figs. 2–5 to exhibit the calculations of $\varepsilon_1(k), \varepsilon_2(k), \varepsilon_3(k)$ and $\varepsilon_4(k)$, respectively.

At first, consider the timing diagram for calculation of $\varepsilon_1(k)$ shown in Fig. 2. In this case, we consider that mobile terminal p resides in the same LA during the time interval (t_c) between two consecutive phone calls to p. Without loss of generality, we suppose that p resides in cell "0" when the previous phone call arrived. After the phone call, p visits successive k cells. p resides in the ith cell for a period $t_{S_i}(0 \le i \le k)$. Let t_s be the interval between the arrival of the previous phone call and the time when p moves out of cell "0". Let $t_{c,i}$ be the interval between when p enters cell i and when the next phone call arrives. Let t_{S_i} be an exponential distributed random variable with rate λ_s.

With the timing diagram shown in Fig. 2, we obtain the possibility $\varepsilon_1(k)$. For brevity, we skip the part of derivation. We note

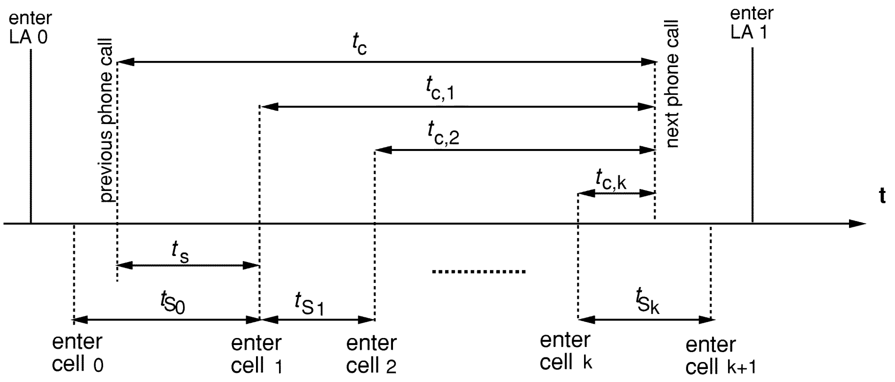

Fig. 2. The timing diagram for calculation of $\varepsilon_1(k)$.

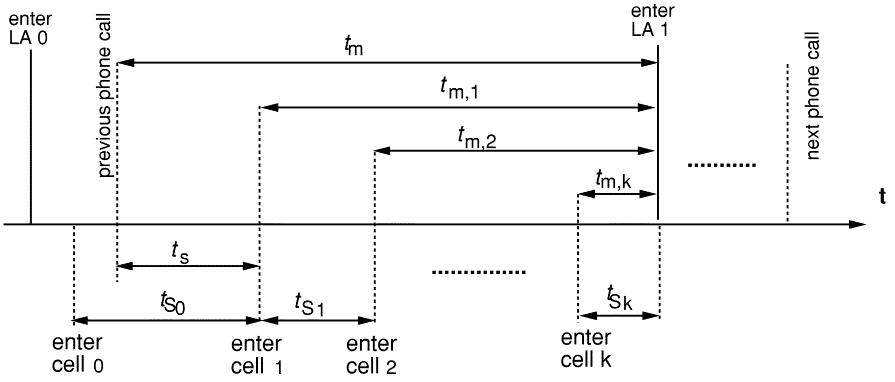

Fig. 3. The timing diagram for calculation of $\varepsilon_2(k)$.

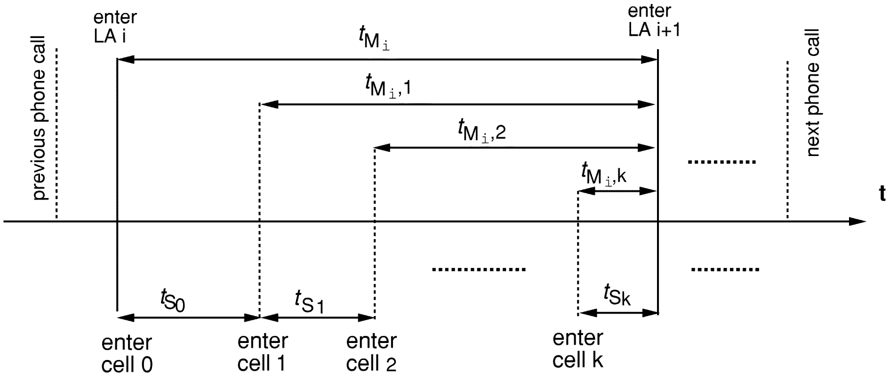

Fig. 4. The timing diagram for calculation of $\varepsilon_3(k)$.

that the possibility can be obtained in a similar fashion as the the calculation of $\alpha(K)$ above

$$\varepsilon_1(k) = \frac{\lambda_c}{\lambda_s + \lambda_c}\left(\frac{\lambda_s}{\lambda_s + \lambda_c}\right)^k, \qquad k = 0, 1, 2, \ldots. \tag{12}$$

By using the timing diagrams in Figs. 3–5, we can also obtain the possibilities $\varepsilon_2(k), \varepsilon_3(k)$ and $\varepsilon_4(k)$, respectively. The processes of these derivations are quite long and complicated. For the brevity, we skip the derivations and just provide the following simple and clear results:

$$\varepsilon_2(k) = \frac{\lambda_m}{\lambda_s + \lambda_m}\left(\frac{\lambda_s}{\lambda_s + \lambda_m}\right)^k, \qquad k = 0, 1, 2, \ldots \tag{13}$$

$$\varepsilon_3(k) = \frac{\lambda_m}{\lambda_s + \lambda_m}\left(\frac{\lambda_s}{\lambda_s + \lambda_m}\right)^k, \qquad k = 0, 1, 2, \ldots \tag{14}$$

$$\varepsilon_4(k) = \frac{\lambda_c}{\lambda_s + \lambda_c}\left(\frac{\lambda_s}{\lambda_s + \lambda_c}\right)^k, \qquad k = 0, 1, 2, \ldots. \tag{15}$$

For the sake of convenience, let

$$\rho_{sc} = \frac{\lambda_s}{\lambda_s + \lambda_c}$$
$$\rho_{sm} = \frac{\lambda_s}{\lambda_s + \lambda_m}.$$

Then we have

$$\varepsilon_1(k) = (1 - \rho_{sc})\rho_{sc}^k \tag{16}$$
$$\varepsilon_2(k) = (1 - \rho_{sm})\rho_{sm}^k \tag{17}$$
$$\varepsilon_3(k) = (1 - \rho_{sm})\rho_{sm}^k = \varepsilon_2(k) \tag{18}$$
$$\varepsilon_4(k) = (1 - \rho_{sc})\rho_{sc}^k = \varepsilon_1(k). \tag{19}$$

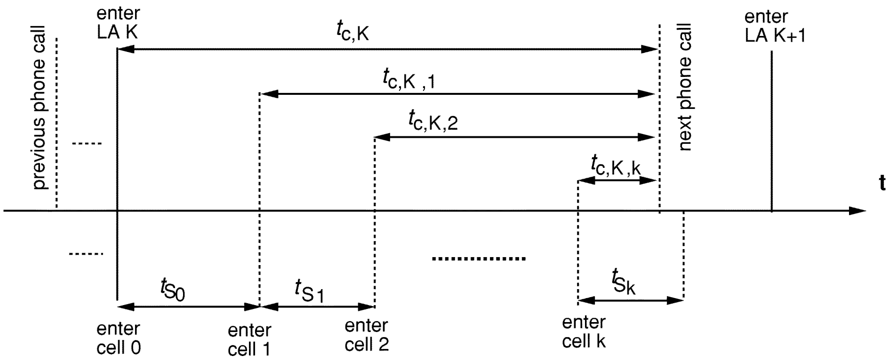

Fig. 5. The timing diagram for calculation of $\varepsilon_4(k)$.

Proceed to obtain the average number of location updates in VLRs when mobile terminal p receives the next phone call in an arbitrary LA LA_K $(K = 0, 1, 2, \ldots)$.

2) Calculation of $n_{\mathrm{vlr},K}$*:* There are two cases needed to be considered for the calculation of the average number of location updates in VLRs per call arrival: Case 1) $K = 0$, i.e., there is no LA boundary crossing and Case 2) $K \geq 1$, i.e., there are $K(K \geq 0)$ LA boundary crossings.

Case 1) $K = 0$.

Substituting (16)–(19) into (11), we obtain

$$\begin{aligned} n_{\mathrm{vlr},0} &= \sum_{l=1}^{\infty} l \sum_{j=ld}^{(l+1)d-1} (1-\rho_{sc})\rho_{sc}^{j} \\ &= \sum_{l=1}^{\infty} l(1-\rho_{sc}) \frac{\rho_{sc}^{ld} - \rho_{sc}^{(l+1)d}}{1-\rho_{sc}} \\ &= \sum_{l=1}^{\infty} l\rho_{sc}^{ld}\left(1-\rho_{sc}^{d}\right) \\ &= \left(1-\rho_{sc}^{d}\right)\rho_{sc}^{d} \sum_{l=1}^{\infty} \left(\left(\rho_{sc}^{d}\right)^{l}\right)' \\ &= \left(1-\rho_{sc}^{d}\right)\rho_{sc}^{d} \left(\frac{\rho_{sc}^{d}}{(1-\rho_{sc}^{d})}\right)' \\ &= \left(1-\rho_{sc}^{d}\right)\rho_{sc}^{d} \frac{1}{(1-\rho_{sc}^{d})^{2}} \\ &= \frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}}. \end{aligned} \tag{20}$$

Case 2) $K = 1, 2, 3, \ldots$. Similarly, to the calculation in relation (20), we obtain each item in $n_{\mathrm{vlr},K}$ in relation (11) as follows:

$$\sum_{l=1}^{\infty} l \sum_{j=ld}^{(l+1)d-1} \varepsilon_2(j) = \frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} \tag{21}$$

$$\sum_{l=1}^{\infty} l \sum_{j=ld}^{(l+1)d-1} \varepsilon_3(j) = \frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} \tag{22}$$

$$\sum_{l=1}^{\infty} l \sum_{j=ld}^{(l+1)d-1} \varepsilon_4(j) = \frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}}. \tag{23}$$

Substituting (21)–(23) into (11), we have

$$\begin{aligned} n_{\mathrm{vlr},K} &= \frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} + (K-1)\frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} + \frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}} \\ &= K\frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} + \frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}}, \quad K = 1, 2, 3, \ldots. \end{aligned} \tag{24}$$

Substituting (24) into (10), we obtain

$$\begin{aligned} n_{\mathrm{vlr}} &= \sum_{K=0}^{\infty} \alpha(K) \cdot n_{\mathrm{vlr},K} \\ &= \sum_{K=0}^{\infty} (1-\rho_{mc})\rho_{mc}^{K} \cdot \left(K\frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} + \frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}}\right) \\ &= (1-\rho_{mc})\frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} \sum_{K=0}^{\infty} K\rho_{mc}^{K} \\ &\quad + (1-\rho_{mc})\frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}} \sum_{K=0}^{\infty} \rho_{mc}^{K} \\ &= \frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} \frac{\rho_{mc}}{1-\rho_{mc}} + \frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}}. \end{aligned} \tag{25}$$

Substituting (25) into (9), finally, the expected cost function of location updates in VLRs per call arrival is obtained as follows:

$$C_{\mathrm{vlr}} = \delta_{\mathrm{vlr}} \left(\frac{\rho_{sm}^{d}}{1-\rho_{sm}^{d}} \frac{\rho_{mc}}{1-\rho_{mc}} + \frac{\rho_{sc}^{d}}{1-\rho_{sc}^{d}}\right). \tag{26}$$

C. Cost of Paging

Let the cost for polling a cell be δ_{poll} $(\delta_{\mathrm{poll}} > 0)$. As was mentioned earlier, all the cells in the PA are paged when an incoming call arrives. In the movement-based location update scheme, the PA is the covering area within a distance $d-1$ from the center cell where the last VLR location update of the mobile terminal occurred, which belongs to the LA where the center cell locates. Note that the covering area within a distance $d-1$ from the center cell may cover more than one LAs, as shown in Fig. 6.

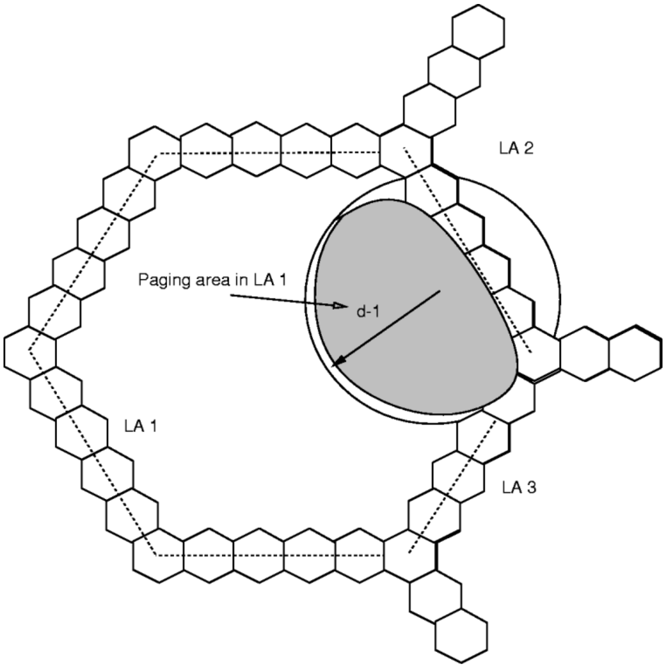

Fig. 6. The PA in an LA with movement-based location update scheme.

Consider the PCS networks with hexagonal cell configurations. The number of cells in the paging process with movement-based location update scheme, denoted by n_{ra}, is upper bounded as follows:

$$n_{\mathrm{ra}} \leq \sum_{j=0}^{d-1} g(j) \tag{27}$$

where $g(j)$ is the number of cells in ring j after the last VLR update before the next phone call arrival and d is the threshold. We note that if the number of cells in an LA n_{la} is much larger than $\sum_{j=0}^{d-1} g(j) (\ll n_{\mathrm{la}})$, then(27) is a good approximation to n_{ra}. We use the upper bound in (27) as an approximation to n_{ra}, i.e.,

$$\begin{aligned} n_{\mathrm{ra}} &\doteq \sum_{i=0}^{d-1} g(i) \\ &= 1 + \sum_{i=1}^{d-1} 6i \\ &= 1 + 3d(d-1). \end{aligned} \tag{28}$$

The expected paging cost per call arrival, denoted by C_p, is given by

$$C_p = \delta_{\mathrm{poll}} \cdot n_{\mathrm{ra}} = \delta_{\mathrm{poll}} \cdot (1 + 3d(d-1)). \tag{29}$$

D. Total Cost for Movement-Based Location Update Scheme

To sum up, substituting (7), (26), and (29) into (1), we obtain the clear and simple formulation for the total cost per call arrival for movement-based location update scheme as follows:

$$\begin{aligned} \mathrm{TC}_{\mathrm{mb}} &= C_{\mathrm{hlr}} + C_{\mathrm{vlr}} + C_p \\ &= \delta_{\mathrm{hlr}} \frac{\lambda_m}{\lambda_c} + \delta_{\mathrm{vlr}} \left(\frac{\rho_{sm}^d}{1-\rho_{sm}^d} \frac{\rho_{mc}}{1-\rho_{mc}} + \frac{\rho_{sc}^d}{1-\rho_{sc}^d} \right) \\ &\quad + \delta_{\mathrm{poll}} (1 + 3d(d-1)). \end{aligned} \tag{30}$$

With the given parameters $\lambda_s, \lambda_c, \lambda_m, \delta_{\mathrm{hlr}}, \delta_{\mathrm{vlr}}, \delta_{\mathrm{poll}}$, and d we can calculate the total cost of a PCS network with(30). With the analytic expression, we can also study the impacts of these parameters.

IV. COST STUDY FOR STATIC LOCATION UPDATE SCHEME

This section derives the cost functions for the static location update scheme used in the existing systems such as GSM and IS-54 [15]. Let $\mathrm{CS}_{\mathrm{hlr}}, \mathrm{CS}_{\mathrm{vlr}}$, and $\mathrm{CS}_{\mathrm{poll}}$ be the costs per call arrival of HLR location updates, VLR location updates, and paging with the static location update scheme, respectively. We express the total cost per call arrival for static location update scheme used in the existing systems, denoted by $\mathrm{TC}_{\mathrm{static}}$ as the sum of $\mathrm{CS}_{\mathrm{hlr}}, \mathrm{CS}_{\mathrm{vlr}}$, and $\mathrm{CS}_{\mathrm{poll}}$

$$\mathrm{TC}_{\mathrm{static}} = \mathrm{CS}_{\mathrm{hlr}} + \mathrm{CS}_{\mathrm{vlr}} + \mathrm{CS}_{\mathrm{poll}}. \tag{31}$$

In the system with static location update scheme, the average number of HLR location updates per call arrival $n_{s\,\mathrm{hlr}}$ and average number of VLR location updates per call arrival $n_{s\,\mathrm{vlr}}$ are the same and equal to the average number of LA boundary crossings between two call arrivals. That is

$$n_{s\,\mathrm{hlr}} = n_{s\,\mathrm{vlr}} = \sum_{i=1}^{\infty} i\alpha(i) = \frac{\lambda_m}{\lambda_c}. \tag{32}$$

Let $\delta_{s\,\mathrm{hlr}}$ and $\delta_{s\,\mathrm{vlr}}$ be the costs for performing a HLR location update and a VLR location update in the static scheme. Since the HLR location update in the static scheme is the same as that in the movement-based scheme, $\delta_{s\,\mathrm{hlr}}$ is the same as that for performing a HLR location update in a movement-based scheme. That is, $\delta_{s\,\mathrm{hlr}} = \delta_{\mathrm{hlr}}$. For the consideration of the cost for performing a VLR location update, we note that a VLR location update in the static scheme includes a registration operation in the new VLR and a deregistration operation in the old VLR. On the other hand, a VLR location update in the movement-based scheme may involve only a registration operation if the mobile terminal stays in the same LA after the VLR location update. Since we assume implicit deregistration, only the registration operation is taken into account. Then, the cost for performing a VLR location update in the static scheme is the same as that in movement-based scheme. That is, $\delta_{s\,\mathrm{vlr}} = \delta_{\mathrm{vlr}}$. From (32), we obtain the expected costs for performing HLR location updates and VLR location updates per call arrival as follows:

$$\begin{aligned} \mathrm{CS}_{\mathrm{hlr}} &= \delta_{s\,\mathrm{hlr}} n_{s\,\mathrm{hlr}} \\ &= \delta_{\mathrm{hlr}} \frac{\lambda_m}{\lambda_c} = C_{\mathrm{hlr}}, \end{aligned} \tag{33}$$

$$\begin{aligned} \mathrm{CS}_{\mathrm{vlr}} &= \delta_{s\,\mathrm{vlr}} n_{s\,\mathrm{vlr}} \\ &= \delta_{\mathrm{vlr}} \frac{\lambda_m}{\lambda_c}. \end{aligned} \tag{34}$$

Furthermore, we note that in the static location update scheme, the system pages all the cells in a LA each time when a call arrives for any mobile terminal currently registered in the LA. So, we have

$$\mathrm{CS}_{\mathrm{poll}} = \delta_{\mathrm{poll}} \cdot n_{\mathrm{la}} \tag{35}$$

where δ_{poll} is the cost for polling a cell and n_{la} is the number of cells in an LA.

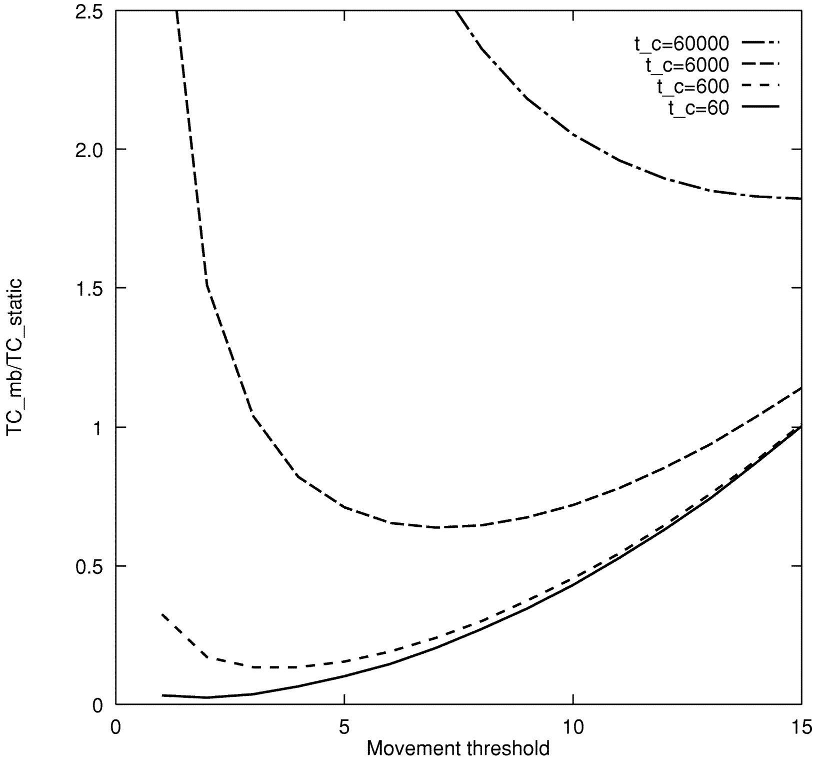

Fig. 7. Cost comparison with $\delta_{\rm hlr} = 20, \delta_{\rm vlr} = 20, \delta_{\rm poll} = 1, r = 15$.

Substituting (33)–(35) into (31), we have

$$\mathrm{TC}_{\rm static} = \delta_{\rm hlr}\frac{\lambda_m}{\lambda_c} + \delta_{\rm vlr}\frac{\lambda_m}{\lambda_c} + \delta_{\rm poll}n_{\rm la}. \quad (36)$$

V. PERFORMANCE EVALUATION AND COMPARISON

The analytic model presented in Sections III and IV allows us to study the performance evaluation and comparison of the movement-based location update scheme and the static location update scheme under various parameters. To demonstrate the effectiveness of the model, we present some typical performance results by using the analytical model.

Performing location updates in HLR and VLR usually spends more wireless and wireline bandwidth utilization and computational resources than polling a cell in PCS networks. The cost for performing a HLR location update and cost for performing a VLR location update should be larger than the cost of polling a cell. The HLR update cost $\delta_{\rm hlr}$, VLR update cost $\delta_{\rm vlr}$, and the polling cost are set to five (5), five (5), and one (1), respectively.

For the purpose of demonstration, consider the shape of LA to be an area of hexagonal cell configuration covering r rings. We call r the radius of an LA. In the movement-based scheme, the value of r shall not be less than the movement threshold d, i.e., $d \le r$.

We first study the impact of changing the location update movement threshold d on the ratio of the total cost per call arrival for the movement-based scheme $\mathrm{TC}_{\rm mb}$ and the total cost per call arrival for the static scheme $\mathrm{TC}_{\rm static}$. Note that for given the size of LAs, $\mathrm{TC}_{\rm static}$ is fixed for different values of d according to (36). Hence, the shape of ratio $\mathrm{TC}_{\rm mb}/\mathrm{TC}_{\rm static}$ is the same as that of $\mathrm{TC}_{\rm mb}$.

For convenience, let $t_s(= 1/\lambda_s)$, $t_m(= 1/\lambda_m)$, and $t_c(= 1/\lambda_c)$ denote the mean cell residence time, the mean LA residence time, and the mean time interval between two consecutive phone call to a mobile terminal, respectively. Note that an LA consists of tens to hundreds of cells. The mean LA residence time t_m shall be larger than the mean cell residence time t_s. For the purpose of demonstration in our numerical examples, t_s and t_m are set to be 120 s (i.e., 2 min) and 1 800 s (i.e., 30 min), respectively.

The mobility of a mobile terminal can be evaluated by the call-to-mobility ratio, which can be defined as the ratio of mean cell residence time and the mean time between two consecutive phone calls to a mobile terminal [3] (i.e., t_s/t_c or λ_c/λ_s) or as the ratio of the mean LA residence time and the mean time between two consecutive phone calls to a mobile terminal [20] (i.e., t_m/t_c or λ_c/λ_m). The smaller the call-to-mobility ratio, the higher the mobility that a mobile user has. For the given mean cell residence time t_s and the mean LA residence time t_m, the shorter the mean time interval t_c, the higher the mobility of a mobile terminal. To study the impact of the mobility and the call arrival patterns, four t_c values, 60 s (1 min), 600 s (10 min), 6000 s (100 min), and 60 000 s (1000 min), are considered in the examples.

Fig. 7 plots the ratio $\mathrm{TC}_{\rm mb}/\mathrm{TC}_{\rm static}$ as the value of the movement threshold $d$increases from 1 to 15 with HLR update cost $\delta_{\rm hlr} = 20$, VLR update cost $\delta_{\rm vlr} = 20$, the cost for polling a cell $\delta_{\rm poll} = 1$, and the radius of an LA $r = 15$. Note that the shape of ratio $\mathrm{TC}_{\rm mb}/\mathrm{TC}_{\rm static}$ is the same as that of $\mathrm{TC}_{\rm mb}$. When the ratio reaches the lowest point, the total cost per call arrival for the movement-based scheme $\mathrm{TC}_{\rm mb}$ also reaches its minimum value. The ratio also shows how much the performance improve-

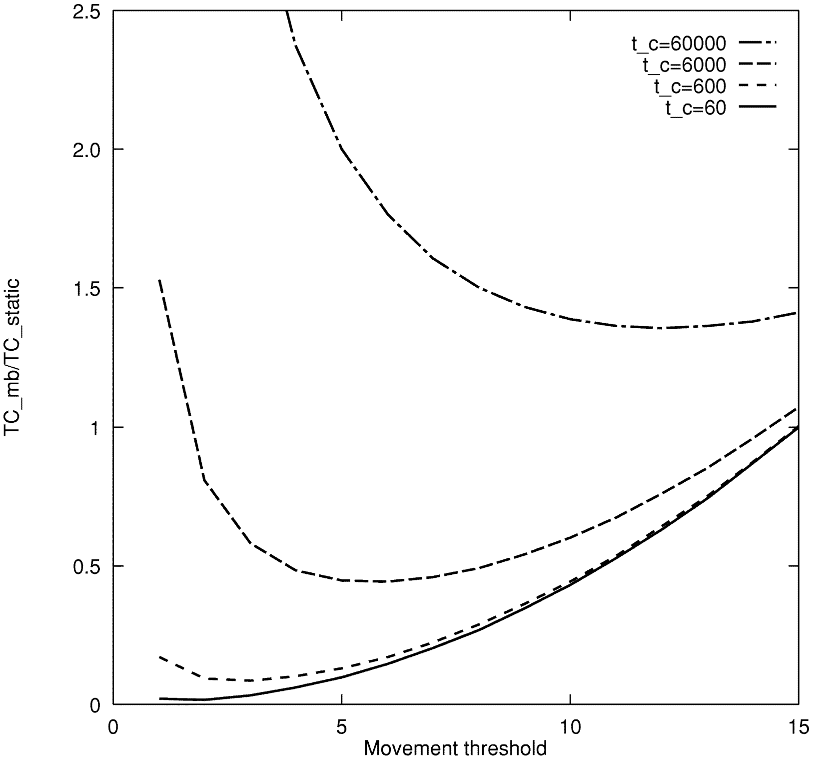

Fig. 8. Cost comparison with $\delta_{\rm hlr} = 20, \delta_{\rm vlr} = 10, \delta_{\rm poll} = 1, r = 15$.

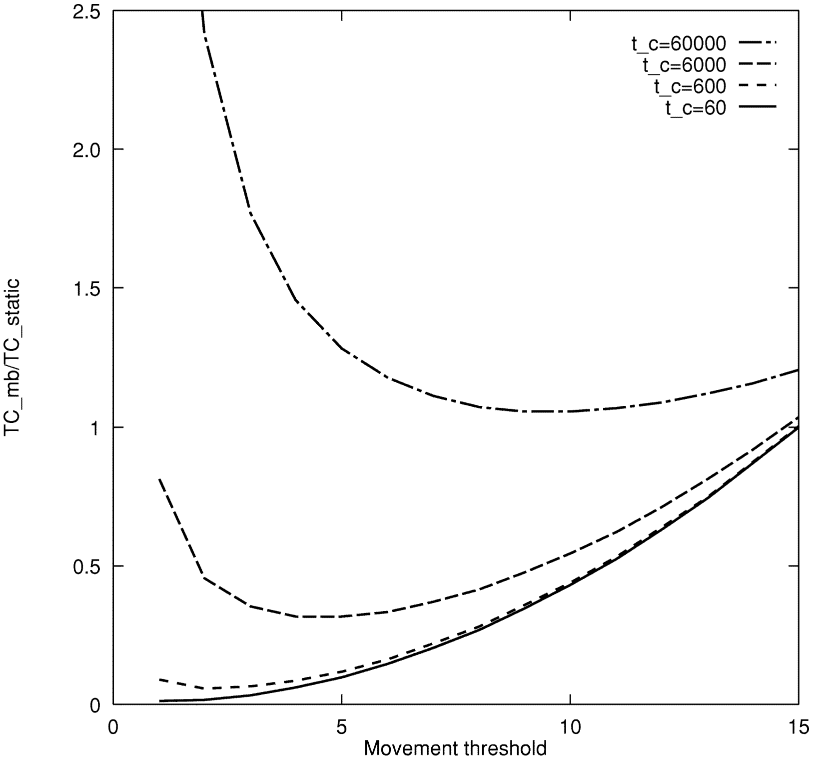

Fig. 9. Cost comparison with $\delta_{\rm hlr} = 20, \delta_{\rm vlr} = 5, \delta_{\rm poll} = 1, r = 15$.

ment obtained by the movement-based scheme. It shows that the performance improvement decreases as t_c increases. Extremely, there is no performance improvement for a very large value of t_c (e.g., $t_c = 60\ 000$ s in Fig. 7). It also shows that the for $t_c = 60$ s, the ratio (or the total cost $\rm TC_{mb}$) is in the lowest point when $d = 2$ and increases as d increases. As t_c increases, the ratio has its lowest point with larger value of d. For example, for $t_c = 600$ s, $t_c = 6\,000$ s, and $t_c = 60\,000$ s, the ratio reaches its lowest point with $d = 3, d = 7$, and $d = 15$, respectively. We define the optimal total cost per call arrival for the move-

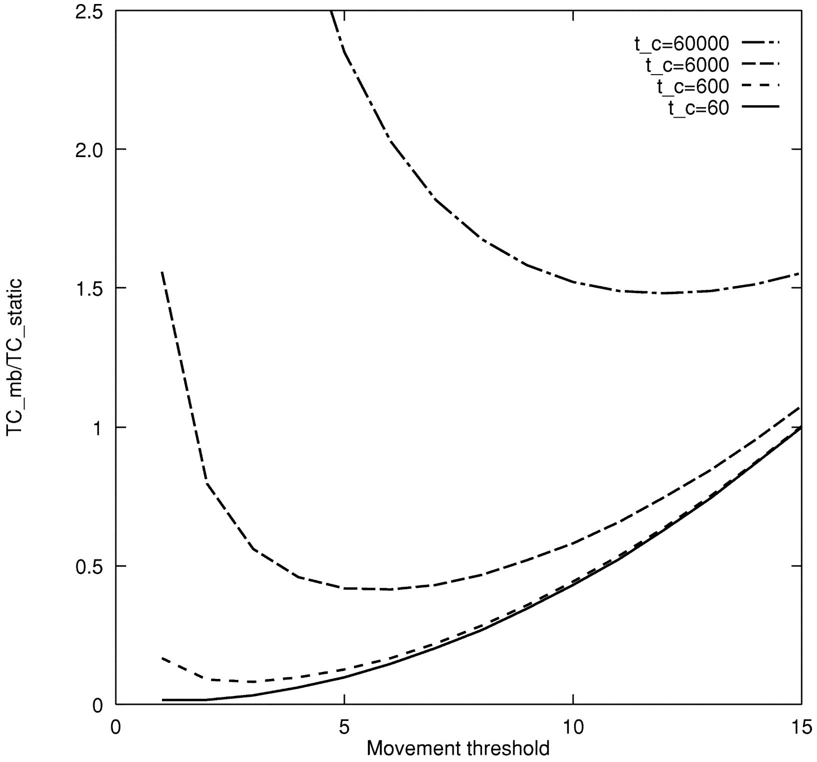

Fig. 10. Cost comparison with $\delta_{\mathrm{hlr}} = 10, \delta_{\mathrm{vlr}} = 10, \delta_{\mathrm{poll}} = 1, r = 15$.

ment-based scheme $\mathrm{TC}^*_{\mathrm{mb}}$ to be the minimum value that can be achieved by adjusting the movement threshold d. Denote by d^* the optimal movement threshold that results in the optimal total cost. The values of $\mathrm{TC}^*_{\mathrm{mb}}$ and d^* depend on the system parameters and, therefore, are mobile terminal dependent. In Fig. 7, $d^* = 2, 3, 7, 15$ for $t_c = 60$ s, 600 s, 6000 s, and 60 000 s, respectively. It can be expected because it is better to not perform the registration operation frequently with the lower mobility (i.e., the larger value of t_c) and vice versa.

Figs. 8–10 show the ratio $\mathrm{TC}_{\mathrm{mb}}/\mathrm{TC}_{\mathrm{static}}$ for smaller values of VLR and HLR update costs. It is shown that as the VLR or HLR update costs decrease, the optimal movement threshold d^* decreases. It is expected because an increase in the movement threshold results in an increase of the PA of the mobile terminal and, thus, decreases the HLR and VLR update costs.

We have conducted the numerical experiments with different system parameters extensively. Due to the limitation of space, we provide the typical results here.

VI. CONCLUSION

In this paper, we developed an analytical model to study the dynamic movement-based location management for PCS networks with HLR/VLR architectures. The obtained analytical formulations are simple and easy to be used. By using the analytical model, we demonstrated performance evaluation and comparison of the movement-based location update scheme and existing static location update scheme under various parameters and mobility and calling patterns. Our model can provide good analysis for the system design and implementation of the dynamic location management for PCS networks. The analysis also provides insights into the structure of the dynamic movement-based location update scheme.

The accuracy of the the analytic model may be verified by the computer simulation or real measurements. Generally speaking, the results obtained by the computer simulation should be the same as that obtained by the analytic method with the same stochastic model and assumptions. Computer simulation may also incorporate more details in studying the performance of PCS networks. We will conduct the computer simulation and real measurements to study the performance as a future work.

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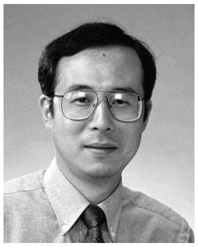

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