A Dynamic Location Management Scheme for Next-Generation Multitier PCS Systems

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***Abstract*—Global wireless networks enable mobile users to communicate regardless of their locations. One of the most important issues is location management in a highly dynamic environment because mobile users may roam between different wireless systems, network operators, and geographical regions. In this paper, a location-tracking mechanism is introduced that consists of intersystem location updates and intersystem paging. Intersystem update is implemented by using the concept of boundary location area, which is determined by a dynamic location update policy in which the velocity and the quality of service are taken into account on a per-user basis. Also, intersystem paging is based on the concept of boundary location register, which is used to maintain the records of mobile users crossing the boundary of systems. This mechanism not only reduces location-tracking costs, but also significantly decreases call-loss rates and average-paging delays. The performance evaluation of the proposed schemes is provided to demonstrate their effectiveness in multitier personal communication systems.**

***Index Terms*—Location management, location update, paging, PCS systems, signaling cost.**

I. INTRODUCTION

FUTURE wireless networks are envisioned as seamless worldwide radio systems, including diverse network backbones ranging from high-capacity picocell networks to terrestrial micro and macro networks as well as large satellite systems [1], [8], [19]. The increasing demands for heterogeneous services necessitate high-quality location management that allows the personal communication service (PCS) networks to locate mobile users roaming across different systems. Location management is also critical to maintain calls in progress as mobile users move into a new service area. In general, location management contains two processes: location update and paging. For stand-alone PCS systems, both of them have been investigated comprehensively over the past decade [2], [5], [6], [22]. In this paper, we focus on the location management schemes for the mobile terminals (MTs) roaming across multitier PCS systems with different technologies or protocols. The registration, call delivery, and handset identity for the heterogeneous PCS systems are discussed in [14]. The registration protocols are modified to accommodate systems using different technologies such as Global System for Mobile Communicators (GSM) and Interim Standard (IS-41). In [24], the authors suggested to "homogenize" the service areas of two adjacent systems by filling the bigger size cells with smaller ones. Accordingly, the location update and paging would be implemented as in one network.

Also, it has been demonstrated in [9] that the roaming across systems imposes a significant increase in signaling traffic. The traffic analysis is based on the interworking of PCS1900 and IS-41 systems by using a dual mode home location registration. In [18], the interworking between cordless and cellular systems, e.g., Digital European Cordless Telephone (DECT) and GSM, is thoroughly investigated. The signaling traffic of intersystem location registration and paging is analyzed based on different system architectures. In [29], the intersystem location registration is studied on GSM/personal digital cellular (PDC) roaming and additional interworking units are proposed to carry out signaling format transformation and authentication. However, in each of the above papers, the signaling costs are not computed based on any specific location update and paging algorithm and the quality of service (QoS) requirements such as call loss and paging delay are not considered.

In this paper, a new location management mechanism is introduced, which is applicable to the integration of heterogeneous systems. A dynamic intersystem location update policy is developed to determine the location update threshold by considering the bandwidth requirement of multimedia service and the MT's velocity. When an MT performs its location update, its roaming information is remained and is used for call delivery. The rest of the paper is organized as follows. In Section II, the system model of multitier PCS systems is described, based on the concept of boundary location area (BLA) and boundary location register (BLR). Then, in Section III, the procedures of intersystem location update and paging are presented, which utilize the BLAs and BLRs to support registration requests and to locate mobile users. In Section IV, the probabilities of intersystem roaming are derived for different mobility models. In Section V, signaling costs, call-loss rates, and paging delays, introduced by intersystem location update and paging, are demonstrated. Finally, in Section VI, numerical results are provided, followed by the conclusion in Section VII.

II. SYSTEM DESCRIPTION

The multitier PCS system we consider is comprised of many systems using different standards such as GSM, IS-95, IS-54/136, and so on. Each system in a given geographical area will typically be supported by a specific network operator. In this section we introduce a system architecture that captures the hierarchical structure of microcells and macrocells.

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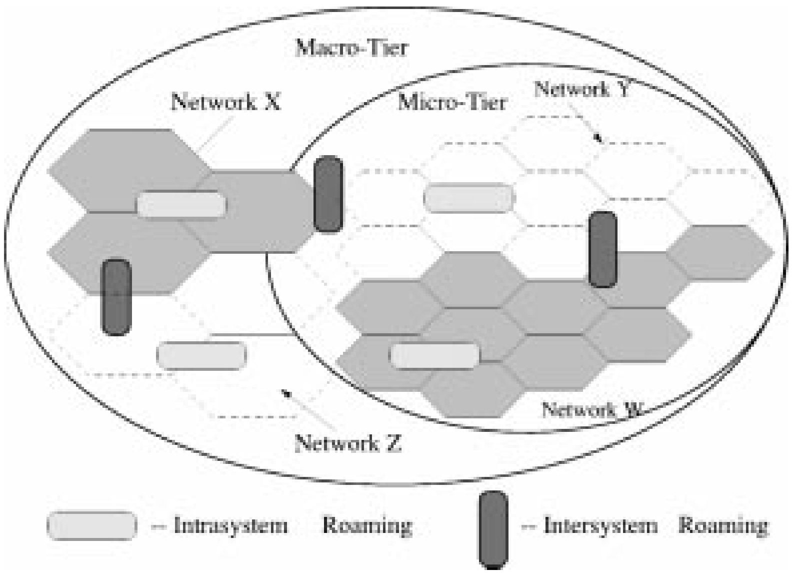


Fig. 1. System architecture of intrasystem and intersystem roaming.

A. System Architecture

In a multitier wireless service area consisting of dissimilar systems, it is desirable to consider some factors which will influence the radio connections of the MTs roaming between different systems. For example, the signaling formats for microcell and macrocell tiers are different. Even in the same tier, the signaling format, user information, and identification authorization are different for systems using different protocols. As shown in Fig. 1, there are two systems Y and W in the microcell tier, which may use different protocols such as DCS1800 and PCS1900. Each hexagon represents a location area (LA) within a stand-alone system and each LA is composed of a cluster of microcells. The terminals are required to update their location information with the system whenever they enter a new LA; therefore, the system knows the residing LA of a terminal all the time. In the macrocell tier there are also two systems X and Z in which different protocols (e.g., GSM and IS-41) are applied. For macrocell systems, one LA can be one macrocell. It is possible that systems X and W, although in different tiers, may employ similar protocols such as IS-95, GSM, or any other protocol. We consider the two-tier model throughout our analysis. However, the proposed scheme is applicable to the multitier scenario by taking pairs of adjacent systems.

There are two types of roaming shown in Fig. 1: *intrasystem* or *intersystem* roaming. Intrasystem roaming refers to an MT's movement between the LAs within a system such as Y and Z. Intersystem roaming refers to the MTs that move between different systems. For example, mobile users may travel from a macrocell system within an IS-41 network to a region that uses GSM standard.

B. Boundary Location Area and Boundary Location Register Concepts

In our context, the location management in multitier PCS systems tackles the intersystem roaming, which includes intersystem location update and paging. The intersystem location update is concerned with updating the location information of an MT performing intersystem roaming. The intersystem paging is concerned with searching for the called terminal roaming between different service areas. The goal of intersystem location management is to reduce the signaling cost while maintaining QoS requirements. For example, reducing call loss is one of the key issues in maintaining the call connection; decreasing the paging delay is critical to reduce the call set-up time.

For intersystem location update, we consider a boundary region called BLA existing at the boundary between two systems in different tiers. As illustrated in Fig. 2, systems X and Y are in the macrocell and microcell tiers, respectively. There is a home location register (HLR) for each system and a user is permanently associated with an HLR in his/her subscribed system. The BLA is controlled by a boundary interworking unit (BIU), which is connected to mobile switching centers (MSCs) and visitor location registers (VLRs) in both systems. The BIU is responsible for retrieving a user's service information and transforming message formats. Also, the BIU is assumed to handle some other issues such as the compatibility of air interfaces and the authentication of mobile users. The BIU is aware of roaming users' information such as the service requirements and bandwidth consumption since all the roaming users are processed through the BIU. Furthermore, the BIU is connected to the LAs adjacent to system Y and it sends the necessary information for intersystem roaming users to the cells in those LAs periodically. The configuration of a BIU depends on the two adjacent systems that this BIU is coordinating. More details can be found in [4], [9], [18], and [29].The BLA is considered as a dynamic region depending on each MTs profile such as speed and bandwidth requirement. When an MT enters the BLA, it sends registration request to the BIU and the BIU forwards this request to the system toward which the MT is moving. By using the BLA concept, an MT is allowed to register and update its location before the MT receives or makes calls in the new system.

In addition to the concept of BLA, we designate a BLR to be embedded in the BIU. A BLR is a database cache to maintain the roaming information of MTs moving between different systems. The roaming information is captured when the MT requests a location registration in the BLA. The BLRs enable the intersystem paging to be implemented within the appropriate

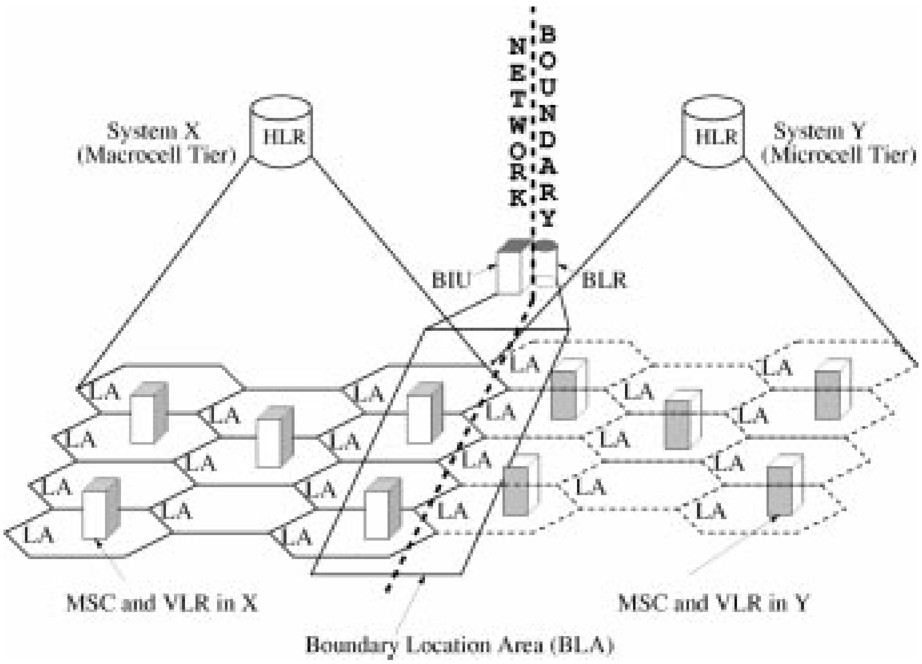


Fig. 2. BLA and BLR.

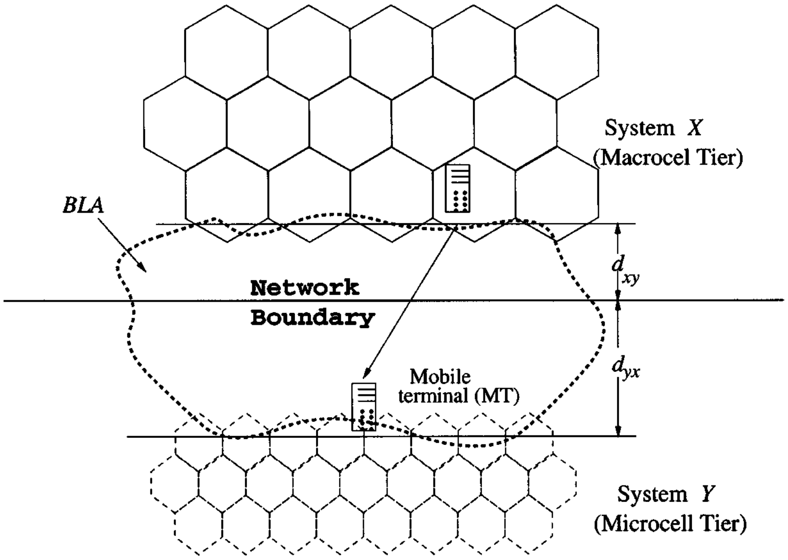


Fig. 3. Location update distance and the concept of BLA.

system in which an MT is currently residing, thus reducing the paging costs. Therefore, the BLR and the BIU are accessible to the two adjacent systems and are collocated to handle the intersystem roaming of MTs. On the contrary, the VLR and the MSC provide roaming information within a system and deal with the intrasystem roaming of MTs. Besides, there is only one BLR and one BIU between a pair of neighboring systems, but there may be many VLRs and MSCs within a stand-alone system.

III. INTERSYSTEM LOCATION UPDATE AND PAGING SCHEMES

When an MT is moving across different systems, it must perform intersystem location update, which is based on the concept of BLA [26]. To locate the MT for call delivery, intersystem paging is realized through BLR.

A. Intersystem Location Update Using BLA Concept

We define the BLA of an MT to be the region in which the MT sends a location registration request to the new system toward which that MT is moving. A new location update mechanism is used such that the MT will report its location when its distance from the boundary is less than *update distance* d_{xy}, determined by (1). This location update scheme guarantees that the MT updates its location information in an area that is within a distance threshold away from the boundary of two systems (tiers), X and Y. For example, Fig. 3 shows the movement path of an MT moving from system X to Y. Assume this MT performed its last location update in the LA within X and its update distance is d_{xy}. The BLA of region within d_{xy} from the boundary in X and the region within d_{yx} in Y, where d_{yx} is the update distance of the MT moving from Y to X.

In order to determine the BLA that is dependent on the MTs update distance, a dynamic location update policy to decide the update distance on a per-user basis. Under this scheme, the update distance d_{xy} for the MT moving from X to Y is based on the following considerations.

1) *Velocity* $\bar{v}$: If an MT is moving very fast, it may arrive at the new system in a short time. Thus, the update distance should be long so that the MT can send the location update message and finish location registration before it enters the new system Y. The *velocity ratio* v_r is defined as $v_r = \bar{v}/v_x$, where v_x is the average speed of all MTs in macrocell system X.
2) *QoS Factor* η: η is the ratio of the bandwidth required by an MT to the bandwidth available in the new system when the multimedia service is provided. If $\eta \leq 1$, it infers that the bandwidth available in Y is more than the bandwidth required, i.e., system Y is ready to maintain the MT's call connection. Thus, the MT can request registration when it is close to the boundary between two networks. If $\eta > 1$, it means that there is not enough bandwidth in Y to support a connection or to make a call. The MT must send a registration request earlier so that the new system will reserve the bandwidth for the MT in order to maintain its call connection.

Combining the above considerations, the *update distance* d_{xy} is determined as

$$d_{xy} = \lceil \eta \cdot v_r \rceil \cdot d_o \tag{1}$$

where η is the QoS factor, v_r is the velocity ratio, d_o is the *basic threshold*, which is the minimum distance from the boundary where an MT must send its registration request for authenticating the identification and transforming signaling formats. d_o is a system parameter depending on the situation in system Y, such as network resources, service specifications, and the network configuration. This intersystem location update scheme is dynamic in the sense that v_r and η are variable over time depending on the network load.

In order for an MT to send registration request from X to Y, the procedure of intersystem location update includes the following steps.

1) In system X, when the MT enters an LA adjoining to Y, it sends a request to the serving base station (BS) to inquire the bandwidth availability in system Y. This information is received by the BS periodically from the BIU that processes MT's radio connections.
2) The BSs in the LA contiguous to Y broadcast their distances from the boundary of two systems (tiers) periodically. Thus, the MT can determine its location with regard to the boundary and the bandwidth availability by receiving the information from the BSs.
3) The MT calculates its update threshold d_{xy} based on the distance and bandwidth information as described before.
4) If the MT finds that it is within the BLA by comparing the location information with update threshold d_{xy}, it sends an intersystem location update request to the BIU on the boundary.
5) The BIU transforms the signaling format, authenticates the user identity, sends registration requests to Y, and updates the MT's profile in the BLR. If this MT needs call connection while roaming, its request is put in the call connection queue in Y.

Note that the new update scheme used for intersystem location update is different from traditional distance-based location update schemes [15], [22] for stand-alone systems. The new location update scheme for intersystem roaming is independent of the design of LAs unlike the other distance-based schemes. Furthermore, the new scheme is dynamically determined from the network load and it takes the MT's movement into account.

B. Intersystem Paging Using BLR Concept

When a call connection request arrives at X, the call will be routed to the last registered LA of called MT. Given that the last registered LA within X is adjacent to Y, the system needs to perform the following steps to locate the MT.

1) Sends a query signal to the BLR between X and Y to obtain the MT's location information. This step is used to ascertain whether the MT has crossed the boundary or not.
2) If the MT has already moved to Y, only the LA in Y needs to be searched. Otherwise, the last registered LA within X will be searched. Within network X or Y, one or multiple polling messages are sent to the cells in the LA according to a specific paging scheme.

As a result, only one system (X or Y) is searched in the paging process for intersystem roaming terminals. This approach will significantly reduce the signaling cost caused by intersystem paging. In particular, it is very suitable for the high-traffic environment because it omits the searching in two adjacent systems. Moreover, since the BLR is an additional level of cache database, it will not affect the original database architecture. Another advantage of the BLR is that it reduces the zigzag effect caused by intersystem roaming. For example, when an MT is moving back and forth on the boundary, it only needs to update the information in the BLR instead of contacting the HLRs. If the new BLR concept is not used, the intersystem paging can still take place. The system will search X first, if the called MT can not be found, then Y will be searched. This method increases the paging cost as well as the paging delay, thus, degrading the system performance, which will be demonstrated in Section VI.

Next, we will evaluate the performance of the proposed location tracking mechanism for two-tier PCS systems. However, as mentioned before, the analytical results can be used for general cases by taking pairs of adjacent systems. The intersystem roaming probabilities during a call connection is determined first and then it is used to find the signaling costs, call-loss rates, and paging delays.

IV. CALCULATION OF INTERSYSTEM ROAMING PROBABILITIES

Intersystem location update and paging costs are associated with the roaming probability from one network to another. The roaming probability can be either experimental results obtained from practical circumstances or numerical results

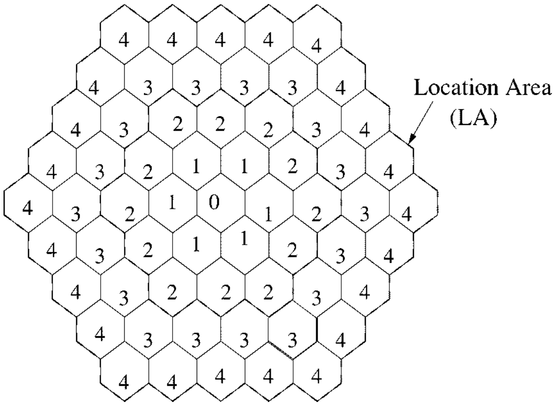


Fig. 4. Number of cells and perimeter of LA.

estimated from theoretical models. In this section, we analyze the roaming probability based on a two-dimensional (2-D) cellular configuration, fluid-flow model for macrocell systems, and random-walk model for microcell systems.

A. 2-D Configuration

We assume that mobile service areas are partitioned into LAs of the same size for both macrocell and microcell tier as shown in Fig. 1. Each cell is surrounded by *rings* of cells as shown in Fig. 4 [10]. The innermost cell "0" is called the center cell; cells labeled "1" form the first ring around cell "0" and so forth. Each ring is labeled according to its distance from the center such that ring r_1 refers to the cells in the first ring away from cell "0." In general, r_k $(k=1,2,\ldots)$ refers to the kth ring away from the center cell. The LA denoted by $A(K)$ is a cluster of cells and the outermost cells are in the r_K ring, e.g., an LA denoted as $A(4)$ in Fig. 4. The number of cells in kth ring is $6\cdot k$. Then, the number of cells $N(K)$ in $A(K)$ is calculated as

$$N(K)=\sum_{k=1}^{K}6\cdot k+1=3(K+1)\cdot K+1 \tag{2}$$

where K denotes the outermost ring within the LA, e.g., $K=4$ for the LA $A(K)$ in Fig. 4.

Similarly, given that the cell radius for system X is $R_x[km]$, we can observe that the perimeter of the center cell is $6R_x$ and the perimeter of the first ring is $18R_x$. The radius R_x is determined based on the number of MTs and bandwidth allocation schemes. The *perimeter* $L_x(K)$ and the *coverage area* $S_x(K)$ of $A(K)$ are

$$\begin{aligned}L_x(K)=&(12K+6)\cdot R_x,\\ S_x(K)=&[3K\cdot(K+1)+1]\cdot 2.6\cdot R_x^2\end{aligned} \tag{3}$$

where $2.6R_x^2$ is the area of each cell in system X.

B. Mobility Model

There are two commonly used mobility models in the literature: fluid-flow model [16], [25], [28] and random-walk model [10], [12]. Of these two models, fluid-flow model is more suitable for users with high mobility, infrequent speed, and direction changes. For pedestrian movements in which mobility is generally confined to a limited geographical area such as residential and business building, random-walk model is more appropriate. Since we are considering intersystem roaming in multitier PCS systems, both fluid-flow and random-walk model are taken into account in the analysis.

Fluid-Flow Model: Under the fluid-flow model, the direction of an MT's movement in the LA is uniformly distributed in the range of $(0,2\pi)$ [23], [28]. Let $\bar{v}$ be average speed (km/hr); $\mathcal{S}(\mathcal{K})$ and $\mathcal{L}(\mathcal{K})$ be area and perimeter of $A(K)$, respectively. The average location update rate $E[R_{A(K)}]$ is equal to the average number of crossings of the boundary of region $A(K)$ per unit time, i.e.,

$$E[R_{A(K)}]=\frac{\bar{v}\cdot\mathcal{L}(\mathcal{K})}{\pi\mathcal{S}(\mathcal{K})} \tag{4}$$

where $\mathcal{S}(\mathcal{K})$ and $\mathcal{L}(\mathcal{K})$ are equal to $S_x(K)$ and $L_x(K)$ in (3) for system X.

Random-Walk Model: The most important characteristic of a random-walk model is that the next position an MT occupies is equal to the previous position plus a random variable whose value is drawn independently from an arbitrary distribution [11]. For the 2-D cellular configuration, if the mobile user is located in a cell of ring k, the probability that a movement will result in an increase or decrease in the distance from the center cell is given by

$$p^{+}(k)=\frac{1}{3}+\frac{1}{6k}\quad\text{and}\quad p^{-}(k)=\frac{1}{3}-\frac{1}{6k}. \tag{5}$$

We define the state $k(k\geq 0)$ of a Markov chain as the distance between the current location of the MT and the center of the LA. This state is equivalent to the index of a ring in which the MT is located. As a result, the MT is said to be in state k if it is currently residing in ring r_k. The transition probabilities $\alpha_{k,k+1}$ and $\beta_{k,k-1}$ represent the probabilities at which the distance of the MT from the center cell of an LA increases and decreases, which are given as

$$\begin{aligned}\alpha_{k,k+1}=&\begin{cases}(1-q), & \text{if } k=0\\ (1-q)\left(\frac{1}{3}+\frac{1}{6k}\right), & \text{if } 1\leq k\leq K\end{cases}\\ \beta_{k,k-1}=&(1-q)\left(\frac{1}{3}-\frac{1}{6k}\right), \quad \text{if } 1\leq k\leq K\end{aligned} \tag{6}$$

where q is the probability that an MT stays in the current cell.

We denote $p_{k,K}$ as the steady-state probability of state k within the LA $A(K)$. Based on the transition probabilities in (6), $p_{k,K}$ can be expressed in terms of the steady state probability $p_{0,K}$ as

$$p_{k,K}=p_{0,K}\prod_{i=0}^{k-1}\frac{\alpha_{i,i+1}}{\beta_{i+1,i}},\quad \text{for } 1\leq k\leq K. \tag{7}$$

With the requirement $\sum_{k=0}^{K}p_{k,K}=1$, $p_{0,K}$ can be expressed by

$$p_{0,K}=\frac{1}{1+\sum_{k=1}^{K}\prod_{i=0}^{k-1}\frac{\alpha_{i,i+1}}{\beta_{i+1,i}}} \tag{8}$$

where $\alpha_{i,i+1}$ and $\beta_{i+1,i}$ are obtained from (6).

C. Calculation of Intersystem Roaming Probabilities

The intersystem roaming probabilities depend on an MT's movement pattern in its original network but not its destination network. Thus, the probability density function (pdf) of the residence time must be determined first. Then the roaming probabilities can be calculated for roaming from a macrocell tier to a microcell tier and vice versa.

The Laplace transform $\widetilde{B}^*_{\widetilde{T}}(s)$ of the residual sojourn time $\widetilde{T}$ within the LA is obtained by

$$\widetilde{B}^*_{\widetilde{T}}(s) = \frac{1 - G^*_T(s)}{s\bar{\tau}} \tag{9}$$

where $G^*_T(s)$ and $\bar{\tau}$ are derived as follows.

We assume that the duration of a call is exponential with the mean value $1/\xi$ and a new call arrival to an MT is a Poisson process with rate λ_n. Thus, the pdf of the interarrival time $f_{\text{inter}}(t_1)$ and call duration time $f_{\text{call}}(t_2)$ are

$$f_{\text{inter}}(t_1) = \lambda_n e^{-\lambda_n t_1} \quad \text{and} \quad f_{\text{call}}(t_2) = e^{-\xi t_2}. \tag{10}$$

Moreover, the pdf of the cell residence time $f_r(t)$ is assumed to be Gamma distribution [10], which has Laplace transform $F_r(s)$ with the mean value $1/\mu$ and the variance V. Then

$$F_r(s) = \left(\frac{\mu\gamma}{s + \mu\gamma}\right)^{\gamma}, \quad \text{where } \gamma = \frac{1}{V\mu^2}. \tag{11}$$

The residence time T of an MT in the LA is the sum of total time that an MT resides in each cell within the LA. If the number of cells passed by an MT is assumed to be a random variable l with uniform distribution on $[1, N(K)]$, the probability mass function $h(l)$ and its Z transform $H(z)$ can be represented as

$$h(l) = \frac{1}{N(K)}, \quad H(z) = \frac{1}{N(K)} \cdot \frac{1 - z^{N(K)}}{1 - z}. \tag{12}$$

Then, the pdf of the residence time $g_T(\tau)$ in an LA has Laplace transform $G^*_T(s)$ as

$$\begin{aligned} G^*_T(s) =& H(z)\mid_{z=F_r(s)} \\ =& \frac{1}{N(K)} \cdot \left(\frac{\mu\gamma}{s+\mu\gamma}\right)^{\gamma} \\ & \cdot \frac{1 - \left(\frac{\mu\gamma}{s+\mu\gamma}\right)^{\gamma N(K)}}{1 - \left(\frac{\mu\gamma}{s+\mu\gamma}\right)^{\gamma}} \end{aligned} \tag{13}$$

where $N(K)$ is computed from (2). From the property of Laplace transform [7], the first-order moment, i.e., the mean value $\bar{\tau}$ of the residence time in the LA, is

$$\bar{\tau} = -\frac{\partial G^*_T(s)}{\partial s}\mid_{s=0} = \frac{N(K)+1}{2\mu}. \tag{14}$$

As shown in Fig. 1, system X and Y are assumed to be in macrocell and microcell tier, respectively. When an MT moves from macrocell-to-microcell tier, i.e., from X to Y, the fluid-flow model described in Section IV-B is applied to estimate the roaming probability. On the other hand, the random-walk model introduced in Section IV-B is used to find the roaming probability of moving from microcell to the macrocell tier (from Y to X).

Macrocell-to-Microcell Tier Roaming Probability: We define $Pr_f[X, Y]$ as the intersystem roaming probability from X to Y during a call, which is equal to the probability that an MT spends more time in an LA than the call holding time

$$\begin{aligned} Pr_f[X,Y] =& Pr[\text{call duration } t_2 > \text{residual time } \widetilde{T}] \\ & \cdot Pr[\text{call arrival during } \widetilde{T}] \\ =& \int_0^{\infty} f_Z(z)dz \\ & \cdot \int_0^{\infty} \lambda_n t \cdot e^{-\lambda_n t} \cdot \tilde{f}(t)dt \end{aligned} \tag{15}$$

where $Z \triangleq t_2 - \widetilde{T}$. $f_Z(z)$ and $\tilde{f}(t)$ are computed from

$$\begin{aligned} f_Z(z) =& \mathcal{L}^{-1}\left\{\frac{\bar{\tau}s}{\xi + s} \cdot \frac{1}{1 - G^*_T(s)}\right\} \\ \tilde{f}(t) =& \mathcal{L}^{-1}\left\{\widetilde{B}^*_{\widetilde{T}}(s)\right\} \end{aligned} \tag{16}$$

where $G^*_T(s)$, $\bar{\tau}$, and $\widetilde{B}^*_{\widetilde{T}}(s)$ are given in (13), (14) and (9), respectively.

Microcell-to-Macrocell Tier Roaming Probability: Let $Pr_r[Y, X]$ denote the intersystem roaming probability for the MTs moving from microcell network X to macrocell network Y. Then, the random-walk model is used to estimate $Pr_r[Y, X]$ as

$$Pr_r[Y, X] = \sum_{k=0}^{K} P_K(k) \cdot Pr[K|k] \cdot \alpha_{K,K+1} \tag{17}$$

where $\alpha_{K,K+1}$ is computed from (6). $P_K(k)$ is the probability that an incoming call arrives when the MT is in state k for a given number of states K. It is computed by

$$P_K(k) = \frac{\bar{t}(k) \cdot p_{k,K}}{\sum_{k=0}^{K} \bar{t}(k) \cdot p_{k,K}} \tag{18}$$

where $p_{k,K}$ is the steady-state probability as in (7) and $\bar{t}(k)$ is the mean residence time in state k that is obtained as

$$\bar{t}(k) = -\frac{\partial [F_r(s)]^{n(k)}}{\partial s}\mid_{s=0}. \tag{19}$$

In this expression, $n(k) = 6k$ is the number of cells included in ring k and $F_r(s)$ is the Laplace transform of the cell residence time in (11).

In addition, $Pr[K|k]$ in (17) is the probability that a call starts in state k and ends up in state K. This probability can be determined by using a continuous-time Markov chain. We define

$$Pr_{k,K}(t) \triangleq P[S(t_0 + t) = K | S(t_0) = k] \tag{20}$$

where $S(t_0)$ is the position of an MT at call-arrival time t_0. Thus, we have

$$Pr[K|k] = \int_0^\infty Pr_{k,K}(t) \cdot \text{Prob[call duration is } t]dt. \quad (21)$$

To calculate $Pr[K|k]$, we denote $\mathbf{Q}$ as the *transition rate matrix*

$$\mathbf{Q} = \begin{bmatrix} \frac{\alpha_{0,1}}{-\bar{t}(0)} & \frac{\alpha_{0,1}}{\bar{t}(0)} & 0 & 0 & \cdots & 0 \\ \frac{\beta_{1,0}}{\bar{t}(1)} & \frac{\alpha_{1,2}+\beta_{1,0}}{-\bar{t}(1)} & \frac{\alpha_{1,2}}{\bar{t}(1)} & 0 & \cdots & 0 \\ 0 & \frac{\beta_{2,1}}{\bar{t}(2)} & \frac{\alpha_{2,3}+\beta_{2,1}}{-\bar{t}(2)} & \frac{\alpha_{2,3}}{\bar{t}(2)} & \cdots & 0 \\ & & \ddots & & \ddots & \\ 0 & \cdots & & & & \cdots \end{bmatrix}. \quad (22)$$

Thus, $Pr[K|k]$ is obtained by substituting (22) and call duration distribution $f_{\text{call}}(t_2)$ into (21)

$$Pr[K|k] = \int_0^\infty \left[e^{-\mathbf{Q}t}\right]_{k,K} \cdot e^{-\xi t} dt. \quad (23)$$

By using *spectral decomposition*, $\mathbf{Q}$ is rewritten as

$$\mathbf{Q} = \mathbf{T \Lambda T}^{-1} \quad (24)$$

where $\mathbf{\Lambda}$ is a diagonal matrix of eigenvalues and $\mathbf{T}$ is a full matrix whose columns are the corresponding eigenvectors so that $\mathbf{Q}{*}\mathbf{T} = \mathbf{T}{*}\mathbf{\Lambda}$ and

$$\mathbf{\Lambda} = \text{diag}[\gamma_1, \gamma_2, \ldots, \gamma_K]. \quad (25)$$

Through some algebra and matrix calculations, $Pr[K|k]$ is obtained as

$$Pr[K|k] = \left[\mathbf{T^{-1}BT}\right]_{k,K} \quad (26)$$

where $\mathbf{T}$ is defined in (24). The matrix $\mathbf{B}$ is determined by

$$\mathbf{B} = \begin{bmatrix} \frac{1}{\gamma_1+\xi} & 0 & 0 & \cdots & 0 \\ 0 & \frac{1}{\gamma_2+\xi} & 0 & \cdots & 0 \\ 0 & 0 & \frac{1}{\gamma_3+\xi} & \cdots & 0 \\ 0 & 0 & 0 & \ddots & \\ 0 & 0 & 0 & \cdots & \frac{1}{\gamma_K+\xi} \end{bmatrix} \quad (27)$$

where $\gamma_1, \gamma_2, \cdots, \gamma_K$ are the eigenvalues of matrix $\mathbf{Q}$ in (25) and ξ is defined in Section IV-C. By substituting (18) and (26) into (17), the intersystem roaming probability from Y to X, $Pr_r[Y, X]$ can be obtained.

V. PERFORMANCE EVALUATION

In this section, we investigate the effects of the proposed intersystem location update and paging scheme. These effects are demonstrated by comparing the signaling costs, call-loss rates, and paging delays resulted from using BLA and BLR with that in a conventional multitier PCS system without using BLA and BLR.

A. Intersystem Location Update Costs

To support the intersystem roaming of a mobile user, additional signaling traffic is required to register from one system to another. The increase in signaling traffic is called *intersystem location update cost* C_u per unit time for intersystem roaming and it is computed from

$$C_u = E[R_{A(K)}] \cdot Pr_s \cdot c_r \quad (28)$$

where c_r is the signaling cost required for each registration and it depends on the location management protocol used for processing a registration. $E[R_{A(K)}]$ is the average location update rate, which is the average number of crossings of the boundary of a region $A(K)$ per unit time. Pr_s is the roaming probability, which can be either $Pr_f[X, Y]$ (15) for moving from X to Y or $Pr_r[Y, X]$ (17) for vice versa.

For an MT moving from a macrocell-to-microcell tier, its mobility pattern is described by fluid-flow model described in Section IV-B. Under this model, location update rate $E[R_{A(K)}]$ is obtained in (4). Before we determine $E[R_{A(K)}]$ for an MT moving from microcell-to-macrocell tier, we need to find the probability of crossing i boundaries of LAs between two call arrivals $\zeta(i, K)$, which is computed by [12]

$$\zeta(i, K) = \begin{cases} 1 - \frac{1}{\theta}\left[1 - G_T^*(\lambda_n)\right], & \text{if } i = 0 \\ \frac{1}{\theta}\left[1 - G_T^*(\lambda_n)\right]^2 \left[G_T^*(\lambda_n)\right]^{i-1}, & \text{if } i > 0. \end{cases} \quad (29)$$

In the above expression, $\theta = \lambda_n \bar{\tau}$ and λ_n is defined in (10). $G_T^*(s)$ is given in (13) and $\bar{\tau}$ is the mean residence time for an MT in region $A(K)$ as given in (14). The average number of crossings of the LA per unit time $E[R_{A(K)}]$ is then obtained as

$$E\left[R_{A(K)}\right] = \lambda_n \cdot i \sum_{i=0}^{\infty} \zeta(i, K). \quad (30)$$

By substituting (17) and (30) into (28), the intersystem location update cost C_u will be obtained.

B. Call-Loss Rates

When an MT moves from one system to another, both new incoming calls and calls in progress must wait for call processing after the intersystem location registration is finished. As a result, the calls can be blocked or lost due to waiting for the location registration. By using the concept of BLA, MTs are allowed to request location registration before they arrive at the new system, which means BLA provides extra time $\overline{\Delta t}$ for a call to wait for processing. When the BLA is not used, a call will be lost if the waiting time $W_t > 0$. However, when the BLA is used, the call will not be lost if W_t is less than or equal to $\overline{\Delta t}$ because this call acquires extra time $\overline{\Delta t}$ to obtain its required bandwidth. Next, we analyze and compare the call-loss rates Pr_{loss} and $\widehat{Pr}_{\text{loss}}$ in the presence and absence of BLA, respectively.

In this context, the calls in progress are assumed to be Poisson process with rate λ_h and are considered to have higher priority than new calls. We also assume that there are Q bandwidth units

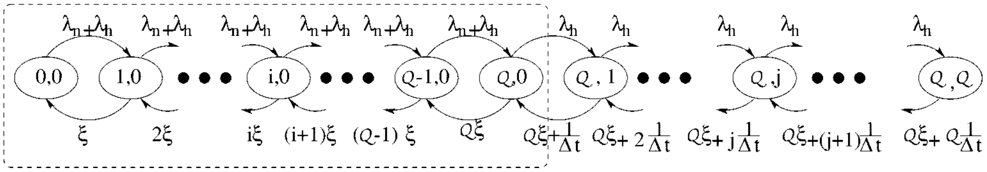


Fig. 5. State transition diagram for queueing system.

available to the new coming MTs from the other systems and each call requires one bandwidth unit, so the call capacity is Q. The new call requests will be blocked when all bandwidth units are occupied and the active calls will be terminated if there are Q calls in waiting.

According to the intersystem location update scheme, the MT requests location update at distance d_{xy} away from the boundary of two systems. This provides extra time $\overline{\Delta t}$ for a call waiting in the queue to be processed. We can obtain $\overline{\Delta t}$ by the following formula

$$\begin{aligned}\overline{\Delta t} =& \frac{1}{\overline{v}} \cdot \sum Pr[\text{update distance is } d_{xy}] \cdot d_{xy} \\ =& \frac{1}{\overline{v}} \cdot \frac{\sum d_{xy} \cdot \mathrm{Num}(d_{xy})}{\mathrm{Num}_{\mathrm{total}}}\end{aligned} \tag{31}$$

where $\mathrm{Num}(d_{xy})$ is the number of MTs having update distance d_{xy} and $\mathrm{Num}_{\mathrm{total}}$ is the total number of MTs requesting location update. The state diagram is shown in Fig. 5, where state (i, j) indicates that there are i active calls and j calls are in the waiting queue. For simplicity, we consider the average waiting time $W_t = \overline{\Delta t}$, so the drop rate from the waiting list is $1/\overline{\Delta t}$.

The state probability $\pi_{i,j}$ is defined as

$$\pi_{i,j} = \begin{cases} Pr[i \text{ calls are active}] & i \leq Q \\ Pr[Q \text{ calls are active and} \\ j \text{ calls are waiting}] & i > Q. \end{cases} \tag{32}$$

The *call-loss rate* Pr_{loss} is then determined by

$$Pr_{\mathrm{loss}} = \frac{1}{\lambda_h} \cdot \sum_{j=1}^{Q} \left(\frac{j}{\overline{\Delta t}} \right) \cdot \pi_{Q,j}. \tag{33}$$

The solutions for $\pi_{i,j}$ can be deduced from the state diagram given in Fig. 5 as

$$\pi_{i,j} = \\ \begin{cases} \pi_{0,0}, & \text{if } i = 0, j = 0 \\ \pi_{0,0} \cdot \frac{(\lambda_n + \lambda_h)^i}{i! \cdot \xi^i}, & \text{if } 0 < i \leq Q, j = 0 \\ \pi_{0,0} \cdot \frac{(\lambda_n + \lambda_h)^Q}{Q! \cdot \xi^Q}, & \text{if } i = Q, j = 0 \\ \pi_{Q,0} \cdot \frac{(\lambda_h)^j}{\left(Q\xi + \frac{1}{\overline{\Delta t}}\right)\left(Q\xi + \frac{2}{\overline{\Delta t}}\right) \cdots \left(Q\xi + \frac{j}{\overline{\Delta t}}\right)}, & \text{if } i = Q, 0 > j \leq Q \end{cases} \tag{34}$$

where $\pi_{0,0}$ is shown in (35) at the bottom of the page.

If BLA is not used for intersystem location update, a call will be lost when there are Q active calls. This is indicated in the Markov chain model in Fig. 5. The number of states is reduced as shown in the dashed box and the queueing system becomes a typical M/M/m/m model. Therefore, the call-loss rate $\widehat{Pr}_{\mathrm{loss}}$ is calculated from *Erlang's loss formula*

$$\widehat{Pr}_{\mathrm{loss}} = \frac{1}{Q!} \cdot \left(\frac{\lambda_n + \lambda_h}{\xi} \right)^Q \frac{1}{\sum_{i=0}^{Q} \left(\frac{\lambda_n + \lambda_h}{\xi} \right)^i \cdot \frac{1}{i!}}. \tag{36}$$

C. Intersystem Paging Costs and Delays

First, we consider the intersystem paging using BLR, i.e., the BLR is queried before searching for a called MT. The *intersystem paging cost* per unit time C_p is the average number of cells required to be searched before the called MT is found

$$C_p = \lambda_n \cdot \{ s_x \cdot (1 - Pr_s) + s_y \cdot Pr_s \} \tag{37}$$

where Pr_s is the intersystem roaming probability obtained in (15) and (17); λ_n is call-arrival rate as defined in (10). s_x and s_y are the paging costs in system X and Y, respectively. These paging costs depend on the specific paging schemes used in each stand-alone system [9], [13], [21]. On the other hand, the *paging cost* of intersystem paging without accessing BLR $\widehat{C}_p$ is

$$\widehat{C}_p = \lambda_n \cdot \{ s_x + s_y \cdot Pr_s \}. \tag{38}$$

The *total signaling cost* including costs of location update and paging C_T for intersystem location management is computed by

$$C_T = C_u + C_p \tag{39}$$

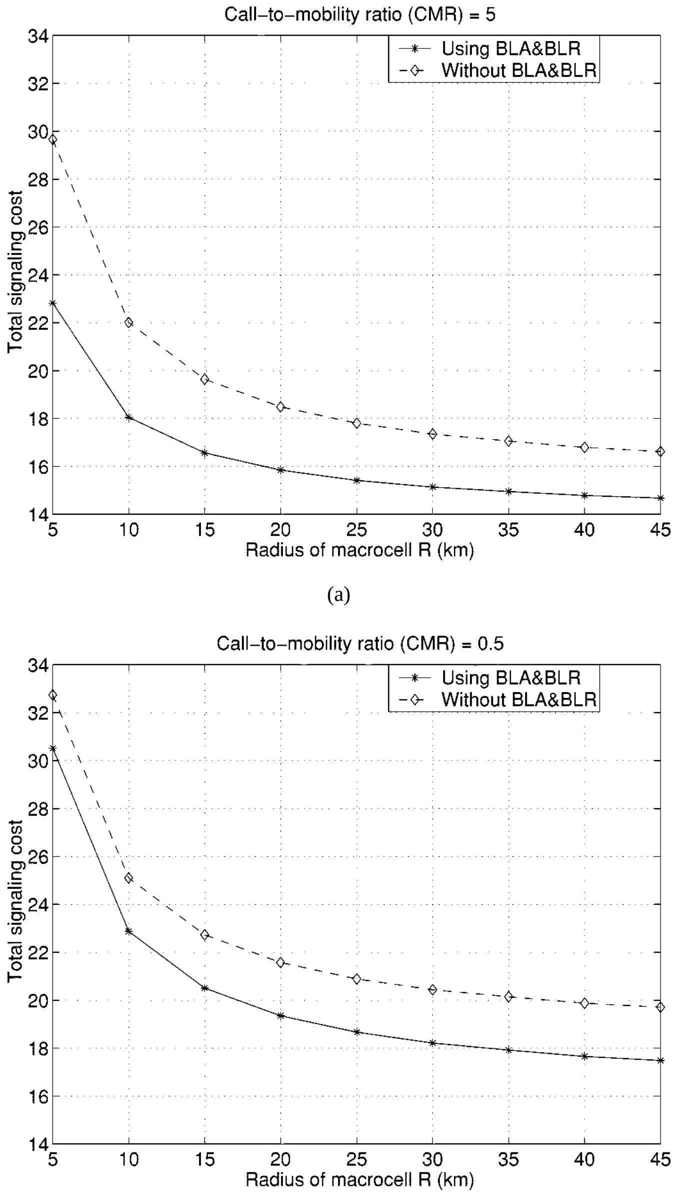
where C_u and C_p are computed from (28) and (37), respectively.

The delay in searching for an MT roaming across different systems is called *intersystem paging delay* D_p

$$D_p = r_x \cdot (1 - Pr_s) + r_y \cdot Pr_s \tag{40}$$

where r_x and r_y are the paging delays in system X and Y, respectively. These paging delays are also determined by the specific paging schemes such as one-step and multistep paging schemes [9], [13], [21]. When BLR is not used, system X is

$$\pi_{0,0} = \frac{1}{\left(1 + \sum_{i=0}^{Q} \frac{(\lambda_n + \lambda_h)^i}{i! \cdot \xi^i} + \frac{(\lambda_n + \lambda_h)^Q}{\xi^Q} \cdot \sum_{j=1}^{Q} \frac{(\lambda_h)^j}{\left(Q\xi + \frac{1}{\overline{\Delta t}}\right)\left(Q\xi + \frac{2}{\overline{\Delta t}}\right) \cdots \left(Q\xi + \frac{j}{\overline{\Delta t}}\right)}\right)}. \tag{35}$$



(a)

(b)

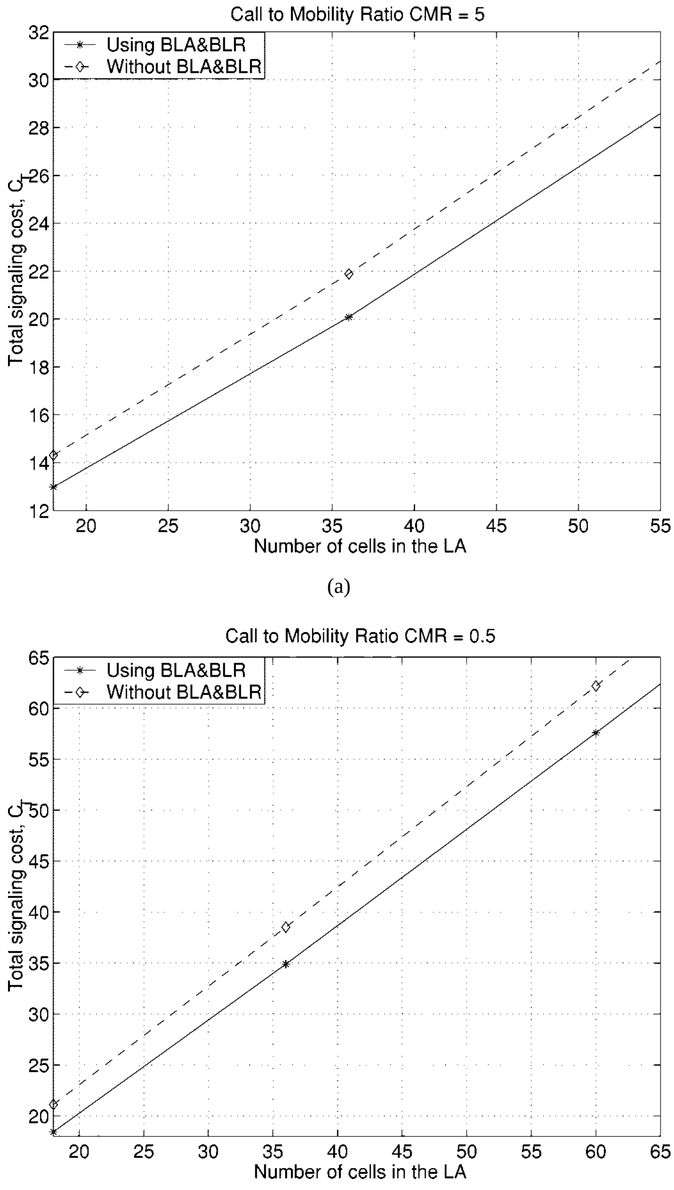
Fig. 6. Total signaling costs of intersystem roaming from macrocell-to-microcell tier. (a) Call-to-mobility ratio (CMR) = 5. (b) Call-to-mobility ratio (CMR) = 0.5.

searched first; if the called MT cannot be found in X, system Y will be searched. Therefore, the intersystem paging delay $\widehat{D}_p$ is

$$\widehat{D}_p = r_x + r_y \cdot Pr_s. \tag{41}$$

VI. NUMERICAL RESULTS

In this section, we provide some numerical evaluation to demonstrate the performance of intersystem roaming supported by BLA and BLR using the results from Section V. As described before, the total signaling costs, call-loss rates and paging delays depend on various parameters in multitier PCS systems. These parameters include update distance d_{xy} or d_{yx} explained in Section III-A; the size of a LA $A(K)$ in terms of ring K, radius R of the cell and registration cost c_r explained in Sections IV-A and V-A; the call-arrival rate λ_n and λ_h; the mean, $1/\mu$ and variance V of the cell residence time as well as the mean $1/\xi$ of the call duration time in Section IV-C; the capacity of calls Q defined in Section V-B; and paging costs s_x and s_y and paging delays r_x and r_y as specified in Section V-C.



(a)

(b)

Fig. 7. Total signaling costs of intersystem roaming from microcell-to-macrocell tier. (a) Call-to-mobility ratio (CMR) = 5. (b) Call-to-mobility ratio (CMR) = 0.5.

TABLE I
CALL-LOSS RATES OF MOVING FROM MICROCELL TO MACROCELL TIER

λ_n	λ_h	ξ	Capacity Q	Pr_{loss}	$\widehat{Pr}_{loss}$
4	4	10	2	9.14%	50%
10	10	10	5	4.91%	20%
20	20	10	8	6.12%	12.5%
20	10	10	8	1.66%	12.5%

TABLE II
CALL-LOSS RATES OF MOVING FROM MACROCELL TO MICROCELL TIER

Radius R (km)		5	10	15	20	25	30	35	40	45
Case A	Pr_{loss}(%)	24.48	20.72	17.94	15.88	14.30	12.90	11.90	10.95	10.11
$\lambda/\xi = 0.8, Q = 2$	$\widehat{Pr}_{loss}$(%)	50	50	50	50	50	50	50	50	50
Case B	Pr_{loss}(%)	13.88	11.38	9.66	8.51	7.53	6.82	6.22	5.68	5.26
$\lambda/\xi = 2.0, Q = 5$	$\widehat{Pr}_{loss}$(%)	20	20	20	20	20	20	20	20	20
Case C	Pr_{loss}(%)	4.78	3.91	3.30	2.89	2.58	2.31	2.10	1.93	1.78
$\lambda/\xi = 3.0, Q = 8$	$\widehat{Pr}_{loss}$(%)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5

A. Total Signaling Costs

First, we investigate the effect of changing the size of LA and call-to-mobility ratio (CMR) defined as λ_n/μ on the total signaling cost C_T in (39). We assume that the cell residence time has the mean $1/\mu$ and the variance $1/\mu^2$ such that $\gamma = 1$ in (11). This results in exponentially distributed cell residence time. The registration cost c_r^x and paging cost s_x are set to eight and ten, respectively, for the MTs moving from an IS-41 network (X) to a PCS1900 network (Y) [9]. For the MTs going to X from Y, the registration cost c_r^y and paging cost s_y are set to six and one, respectively, and the one-step paging scheme is used within each system. The basic distance d_o is set to $0.1R$ for the macrocell tier and to R for the microcell tier, respectively. The velocity ratio v_r is assumed to be uniformly distributed in [0.7, 1.3], which means an MT may change its velocity by up to 30% of the average velocity in the system. The QoS factor η is assumed to be uniformly distributed in [0.1, 1.9]. To demonstrate the effect of changing the mobility and call-arrival patterns, two CMR values of five and 0.5 are considered.

Figs. 6 and 7 show that the value of C_T is a function of the size of LA and CMRs. The value of C_T increases as the CMR decreases because the decrease in CMR results in higher intersystem roaming probability during the connection of a call and, thus, increases the total signaling cost. For example, C_T in Fig. 6(b) are higher than that in Fig. 6(a). A similar trend is also observed in Fig. 7. Our results demonstrate that C_T is reduced by up to 18% using BLA and BLR for the MTs moving from macrocell-to-microcell tier and up to 14% for the MTs moving from microcell-to-macrocell tier. The difference between the cost reductions in two movement directions is caused by the different mobility patterns in macrocell and microcell tiers.

Note that, in Fig. 6, the value of C_T decreases as the radius of macrocell increases. However, in Fig. 7, C_T increases as the size of LA (ring K) increases. This observation results from the one-step paging scheme being used in macrocell and microcell systems. In the microcell system, paging request is broadcast to all cells within the LA, thus causing high signaling costs. Rather, the paging request is broadcast in only one macrocell for the macrocell system. Consequently, the paging cost in the macrocell tier is low. Actually, optimizing paging costs in PCS systems is another research subject as addressed in [3], [17], [20], and [27] and is not within the scope of this paper.

B. Call-Loss Rates

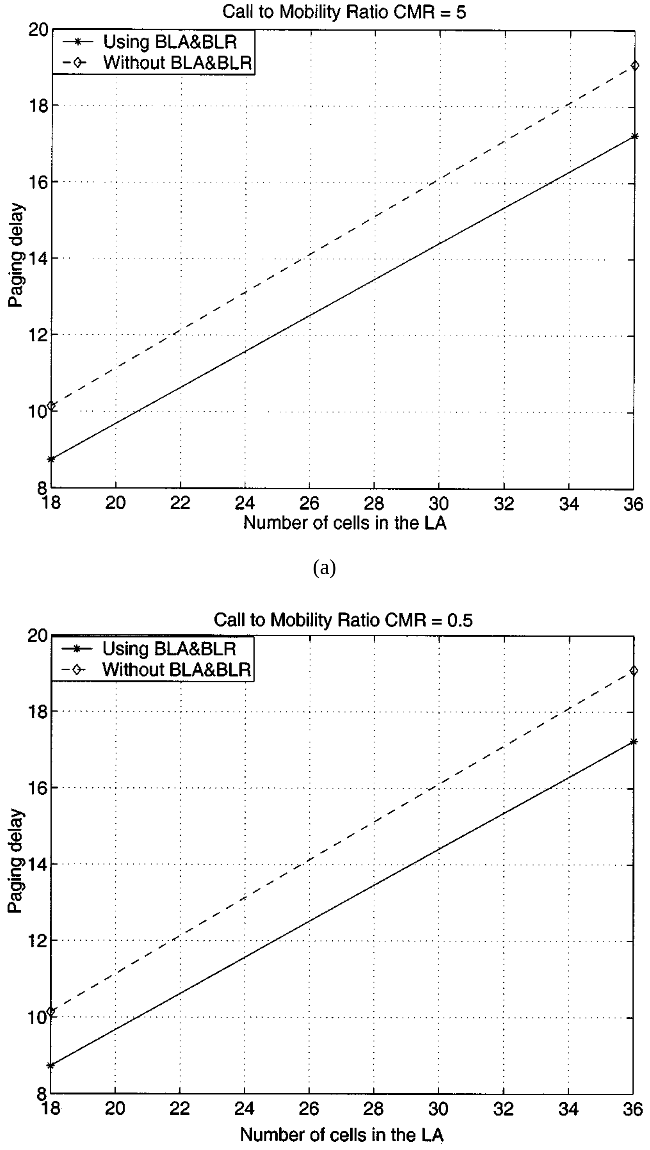
From (33) and (36), Pr_{loss} and $\widehat{Pr}_{\text{loss}}$ are obtained for an MT moving from a microcell (Y) to a macrocell (X) tier as shown in Table I. We observe that the reduction in call-loss rate is very noticeable given that the capacity Q is scarce and the volume of traffic is high. The call-loss rates can be reduced by up to 88% when BLA and BLR are used.

Three cases are considered in evaluating the call-loss rates for MTs moving from macrocell (X) to microcell (Y) tier as shown in Table II. From Table II, where $\lambda = \lambda_n + \lambda_h$, we find that the call loss is reduced considerably for each case. As the capacity Q increases, the call-loss rates decrease irrespective of the use of BLA. However, the call-loss rates are when the capacity Q is small such as in Case A. In addition, the call-loss rates are reduced further if the radius of the macrocell R is large. It can be concluded that the overall improvement in call-loss rate can be up to 87%. These results demonstrate the effectiveness of the intersystem location update scheme in reducing call loss.

C. Paging Delays

Here, we consider two cases: one-step paging and sequential paging (multistep paging scheme) [21] to evaluate paging delays. When the one-step paging scheme is used, paging delay in each LA is equal to one, which means that the system must be able to locate the MT in one *polling cycle*. A polling cycle is the time from when a paging message is sent to the response is received. Therefore, the average paging delay is always one when BLR is used for intersystem paging. Our results show that the overall paging delays are reduced by up to 22% when CMR is five for MTs moving from macrocell-to-microcell tier and they are reduced up to 14% for MTs moving from microcell-to-macrocell tier.

If the sequential paging scheme is used in microcell system, the paging delays are more than one polling cycle and they depend on the number of cells included in an LA. We assume the location cell is the same for all cells. Under the sequential paging scheme, the cells are searched one by one in decreasing order of location probabilities. Fig. 8 shows the paging delays for CMR $= 5$ and CMR $= 0.5$. The paging delays are reduced by using BLR even though the size of LA increases, yet they are less sensitive to the changes of CMR as shown in Fig. 8. These results exemplify that the proposed intersystem paging scheme is capable of reducing paging delays even though different paging schemes are used in stand-alone systems.



(a)

(b)

Fig. 8. Paging delays of moving from microcell tier to macrocell tier. (a) Call-to-mobility ratio (CMR) = 5. (b) Call-to-mobility ratio (CMR) = 0.5.

VII. CONCLUSION

In this paper, we introduced a location tracking mechanism for multitier PCS systems that combines intersystem location update and paging schemes. The intersystem location update is implemented based on the concept of BLA, which is dynamically determined by the MT's velocity and network load. This process greatly reduces the call-loss rates. The intersystem paging is realized through a cache database named BLR, which maintains the roaming information of MTs moving across two systems. It is demonstrated that when CMR becomes smaller, the signaling costs and paging delays are reduced, even though the LA becomes larger. In summary, the numerical results demonstrate that the proposed intersystem location update and paging schemes result in significant performance improvements for the multitier PCS systems.

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