Local Anchor Scheme for Reducing Signaling Costs in Personal Communications Networks

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***Abstract*—A personal communications network (PCN) location tracking scheme called *local anchoring* is introduced which reduces the signaling cost as compared to the location management strategy proposed in the IS-41 standard. Local anchoring reduces the number of location registration messages between the home location register (HLR) and the visitor location registers (VLR's) in a way that location change is reported to a nearby VLR called the local anchor (LA) instead of to the HLR. This method successfully reduces the cost for location tracking when the call arrival rate is low relative to the mobility rate and the cost for location registration is high. A dynamic local anchoring mechanism is then introduced which dynamically selects the LA such that the expected cost for location registration and call delivery can be further reduced. It is demonstrated that the cost of dynamic local anchoring is always lower than or equal to that of the IS-41 scheme.**

I. Introduction

PERSONAL communications networks (PCN's) provide wireless communication services to subscribers that travel within the network coverage area. In order to correctly route incoming calls to a mobile terminal, a number of methods are proposed to keep track of the up-to-date location of each mobile terminal [6], [8]. Two standards currently exist for PCN location management: IS-41 [1], [8] and GSM [8], [9]. The IS-41 is commonly used in North America while the GSM is popular in Europe. Both the IS-41 and the GSM are based on a two-level database hierarchy. Two types of database, home location register (HLR) and visitor location register (VLR), are used to store the location information of the mobile terminals. Fig. 1 shows the basic architecture of a PCN under this two-level hierarchy. The whole PCN coverage area is divided into cells. Each mobile terminal within a cell communicates with the network through a base station which is installed inside the cell. These cells are grouped together to form larger areas called registration areas (RA's). All base stations belonging to a giving RA are wired to a mobile switching center (MSC) which serves as the interface between the wireless and the wireline portions of the PCN. In Fig. 1, we assume that a VLR co-locates with the MSC. Depending on the network configuration, there may exist one or more HLR's in the PCN. Fig. 1 assumes that the MSC's, the VLR's, and the HLR are interconnected by the public switched telephone network (PSTN).

Manuscript received May 17, 1995; revised April 25, 1996; approved by IEEE/ACM Transactions on Networking Editor K. K. Sabnani.

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Publisher Item Identifier S 1063-6692(96)07568-1.

The HLR stores the user profiles of its assigned subscribers. These user profiles contain information such as the type of services subscribed, the quality-of-service (QoS) requirements and the current location of the mobile terminals. Each VLR stores replications of the user profiles of the subscribers currently residing in its associated RA. In order to effectively locate a mobile terminal when a call arrives, each mobile terminal is required to report its location whenever it enters a new RA. We call this reporting process location update. On receiving a location update message, the MSC updates its associated VLR and transmits the new location information to the HLR. We call this database update process location registration. The HLR will acknowledge the MSC for the successful registration and it will also deregister the mobile terminal at the old RA. In order to locate a mobile terminal for call delivery, the HLR is queried to determine the serving MSC of the target mobile terminal. The HLR then sends a message to this MSC which, in turn, will determine the serving base station of the mobile terminal by paging all cells within its associated RA.

This location tracking scheme requires the exchange of signaling messages between the HLR and the new and old MSC's whenever the mobile terminal crosses an RA boundary. This may result in significant traffic load to the network especially when the current location of the mobile terminal is far away from its HLR and the mobile terminal is making frequent movements among RA's. Besides, the HLR may experience excessively high database access traffic as it is involved in every location registration and call delivery. This may result in increased connection set up delay during periods of high network utilization.

A number of efforts have been reported to reduce the signaling load due to location tracking. A caching strategy is introduced in [4] which reduces the signaling cost for call delivery by reusing the cached information about a called user's location from a previous call. In [7], a threshold scheme is introduced that dynamically determines the time when a cache record becomes obsolete. In [3], a location forwarding strategy is proposed to reduce the signaling cost for location registration. Whenever a mobile terminal crosses an RA boundary, a pointer is set up at the old VLR indicating the new VLR of the mobile terminal. When an incoming call arrives, the HLR determines the serving VLR of the mobile terminal by transversing the pointer chain. Location registration is performed when the pointer chain exceeds a pre-defined length K. This method successfully reduces the location tracking cost as compared to the IS-41 scheme when

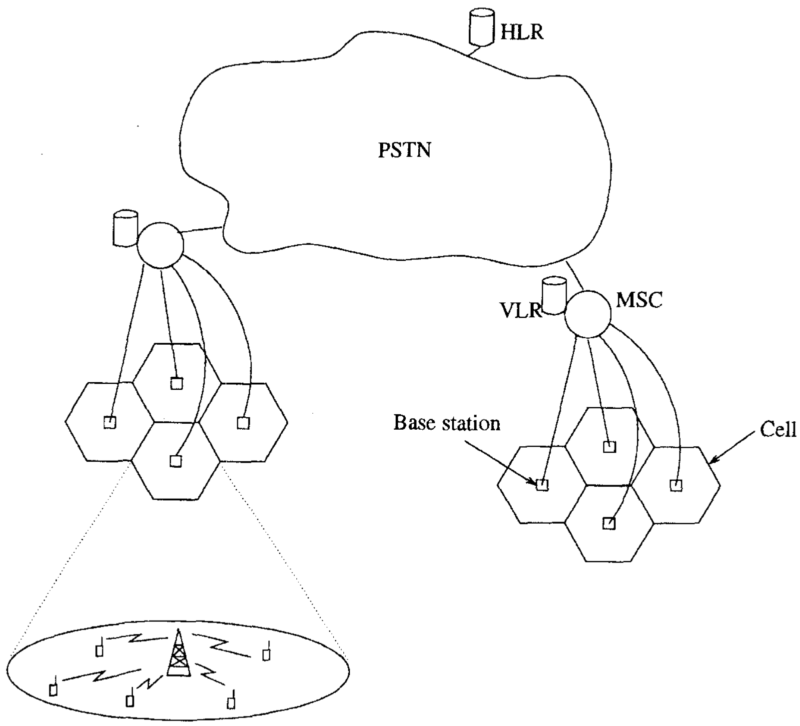

Fig. 1. PCN architecture.

the call to mobility ratio is low. However, a maximum of $K+1$ VLR queries have to be performed in order to locate the mobile terminal. This introduces additional delay in the call delivery process. Moreover, location registration must be performed after K RA crossings because of maximum delay requirement even though it may be more cost effective not to register. We will compare in more detail our proposed scheme with this location forwarding strategy in Section VI.

In this paper, we propose a scheme called local anchoring. We believe that location registration should be localized such that transmission of registration messages to a remote HLR is greatly reduced. Based on the mobility and the location of a mobile terminal, a VLR close to the mobile terminal is selected as the LA. Up-to-date location information of the mobile terminal is reported only to this LA. The HLR records the ID of the current LA of each of its assigned mobile terminal. When an incoming call arrives, the HLR queries the LA which, in turn, queries the serving VLR in order to determine the current location of the mobile terminal. Two schemes for selecting the LA are proposed in Section III. It will be shown that when the call arrival rate of the mobile terminal is high relative to the mobility rate or when the HLR access is not expensive, it may not be cost effective to use local anchoring. We will describe in Section V a dynamic local anchoring scheme that can dynamically determine whether the mobile terminal should report a location change to the LA or directly to the HLR after each movement. Dynamic local anchoring can achieve a lower location tracking cost as compared to that of the IS-41 scheme.

This paper is organized as follows. In Section II, we describe the reference PCN architecture. Section III introduces the local anchoring mechanism. An analytical model for local anchoring is given in Section IV and the performance of local anchoring is compared to that of the IS-41 scheme. Section V proposes a scheme for dynamically selecting the anchor VLR and studies the performance of this dynamic scheme. In Section VI, we compare the proposed local anchoring scheme with the location forwarding strategy as introduced in [3]. The conclusion is given in Section VII.

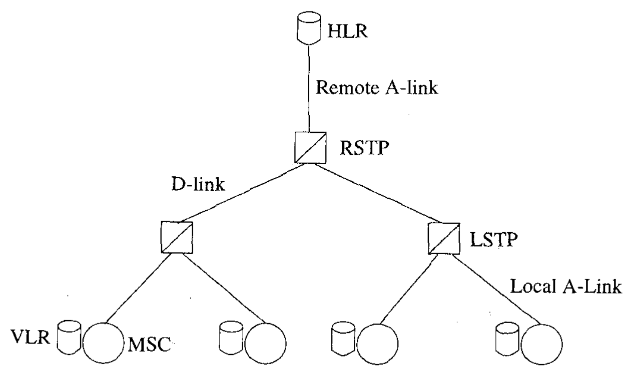

Fig. 2. Reference architecture.

II. System Description

Fig. 2 shows the reference PCN signaling networking architecture assumed throughout this paper. According to Fig. 2, each MSC/VLR is connected to the rest of the network through a local signal transfer point (LSTP) while all the LSTP's belonging to the same region are connected to a regional signal transfer point (RSTP). The LSTP and the RSTP are packet

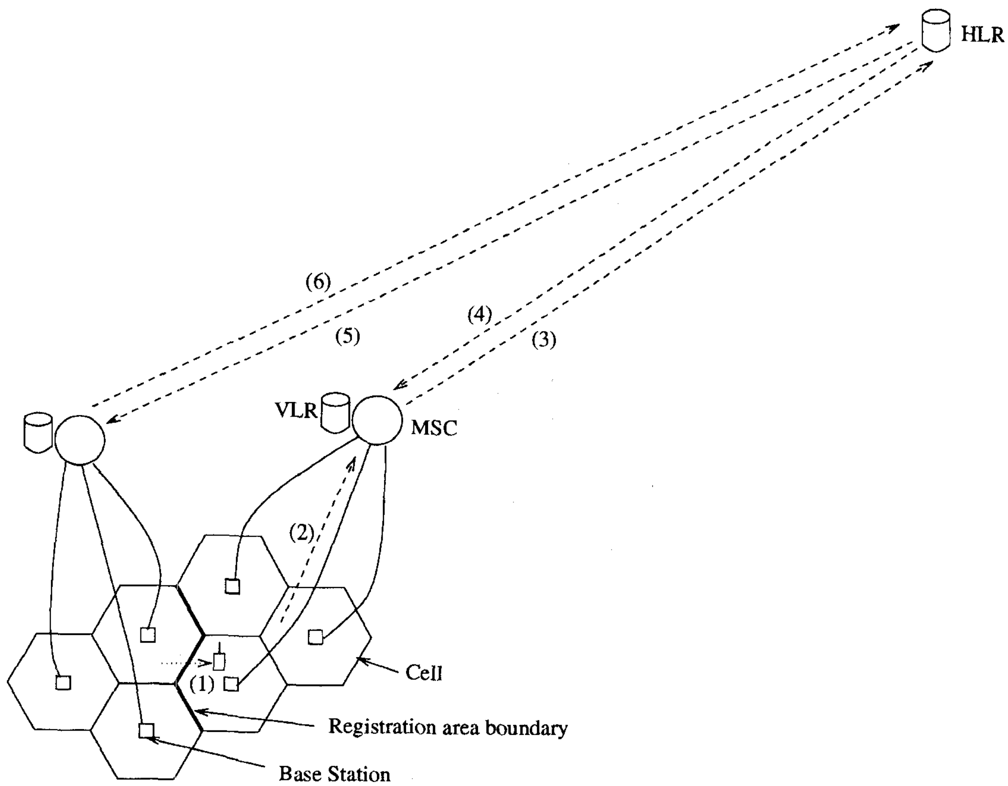

Fig. 3. Location registration.

switches and their major function is the routing of signaling messages. We call the area covered by all RA's belonging to an LSTP the LSTP region. The MSC/VLR is connected to the LSTP through a local A-link while the LSTP is connected to the RSTP through a D-link. The RSTP is, in turn, connected to the HLR through the remote A-link. Depending on the locations of the MSC's, the VLR's, and the HLR, these links may go through a number of intermediate switches and the cost for sending a signaling message through these links may vary. In this paper, we do not discriminate links of the same type such that the cost for sending a message through a selected type of link is constant regardless of the actual length of the link. We also assume the costs for accessing the VLR's at different RA's to be the same.

Procedures for location registration and call delivery are proposed in the IS-41 standard [1], [8]. According to the IS-41 location strategy, the HLR always know exactly the ID of the serving MSC of a mobile terminal. We outline the major steps of the IS-41 location registration scheme as follows (see Fig. 3).

1) The mobile terminal moves into a new RA and sends a location update message to the nearby base station.
2) The base station forwards this message to the new serving MSC.
3) The new MSC updates its associated VLR, indicating that the mobile terminal is now residing in its services area and sends a location registration message to the HLR.
4) The HLR sends a registration acknowledgment message to the new MSC/VLR together with a copy of the subscriber's user profile.
5) The HLR sends a registration cancellation message to the old MSC/VLR.
6) The old MSC removes the record for the mobile terminal at its associated VLR and sends a cancellation acknowledgment message to the HLR.

The IS-41 call delivery scheme is outlined as follows (see Fig. 4).

1) The calling mobile terminal sends a call initiation signal to its serving MSC through the nearby base station.
2) The MSC of the calling mobile terminal sends a location request message to the HLR of the mobile terminal.
3) The HLR determines the current serving MSC of the called mobile terminal and sends a route request message to this MSC.
4) The MSC determines the cell location of the called mobile terminal and assigns a temporary location directory number (TLDN) to the called mobile terminal. The MSC then sends this TLDN to the HLR.
5) The HLR sends the TLDN to the MSC of the calling mobile terminal. The calling MSC can now set up a connection to the called MSC through the PSTN.

III. The Local Anchoring Mechanism

We assume throughout this paper that there is a VLR assigned to each RA. According to the IS-41 location strategy as

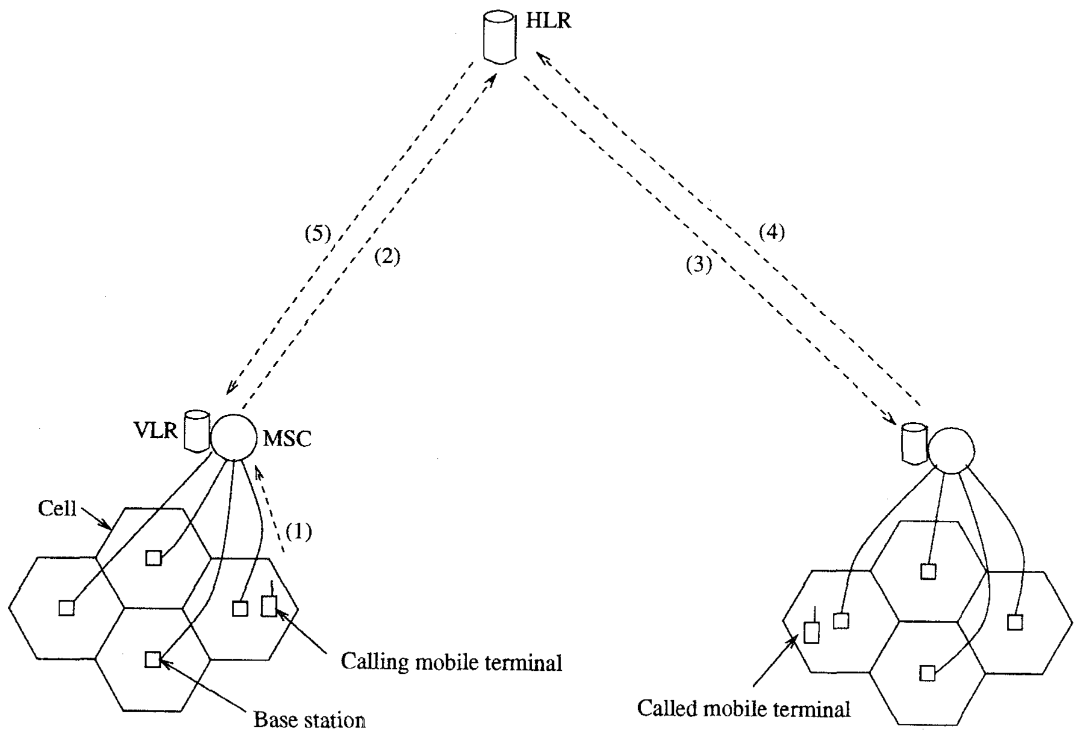

Fig. 4. Call delivery.

described in Section II, the MSC sends a location registration message to the HLR whenever the mobile terminal moves to a new RA. If the mobility of the mobile terminal is high while it is located relatively far away from its assigned HLR, an excessive amount of location registration messages are transmitted across long distance between the serving MSC and the HLR. For example, if the HLR of the mobile terminal is located in Atlanta while the mobile terminal is roaming in California, a location registration message is sent from the serving MSC in California to the HLR in Atlanta whenever the mobile terminal crosses an RA boundary. Even if the mobile terminal is roaming in an RA that is much closer to its home location, location registration may still generate significant load to the network. For example, the HLR for a particular terminal may be installed at a centralized location (such as San Jose, CA) while the subscriber lives in another area (such as Sacramento, CA). A location registration message is sent from the subscriber's home location to the remote centralized HLR whenever the subscriber moves across an RA boundary in his/her home area.

Here we introduce a location registration scheme which reduces the signaling traffic by removing the need to transmit location registration messages to the HLR when the mobile terminal crosses an RA boundary. Under this scheme, the MSC of the newly entered RA registers the mobile terminal's location at a nearby VLR. We call this VLR the LA and its associated LSTP region the anchor LSTP region. Each mobile terminal may have a different LA and the LA for a mobile terminal may be changed from time to time. Once a VLR is selected as the LA for a particular mobile terminal, an entry is set up in a table at this VLR indicating the current serving MSC/VLR for the mobile terminal. The HLR of the mobile terminal will then be informed of the ID of the new LA. We have to note that the LA of a mobile terminal may also be the serving VLR of the same mobile terminal. There are many ways for selecting the LA. One method is to designate a specific VLR in each LSTP region as the LA for all mobile terminals in that LSTP region. However, this method may place significant signaling load to the selected VLR. We believe that the signaling load should be distributed more evenly among all VLR's in each LSTP region. The IS-41 location strategy is a special case of local anchoring which selects a new LA after every RA boundary crossing such that the LA is always the same as the serving VLR. In this paper, we introduce two methods for selecting the LA.

1) Static Local Anchoring (SL): The location of the mobile terminal is never reported to the HLR. The serving VLR of the mobile terminal during the last call arrival is selected as the LA.

2) Dynamic Local Anchoring (DL): After a movement, the serving VLR of the mobile terminal becomes the LA if this will result in lower expected cost. Otherwise, the LA is not changed. After a call arrival, the serving VLR of the mobile terminal becomes the LA.

Both SL and DL select the serving VLR during the last call arrival as the new LA. This is reasonable because the HLR knows the location of the mobile terminal after call delivery and the HLR should not query the old LA in order to determine the serving VLR when the next call arrives. The performance of SL is studied in Section IV. It is demonstrated that this selection of LA produces good saving in location tracking cost except when the call arrival rate is high compared to

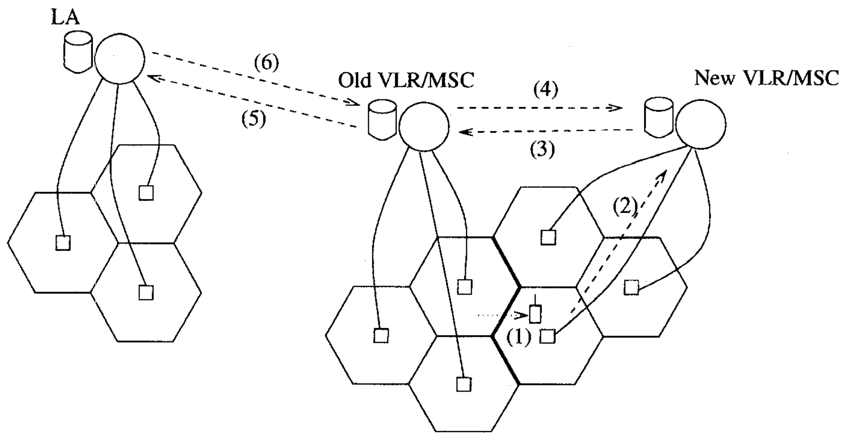

Fig. 5. Reporting location change to the LA.

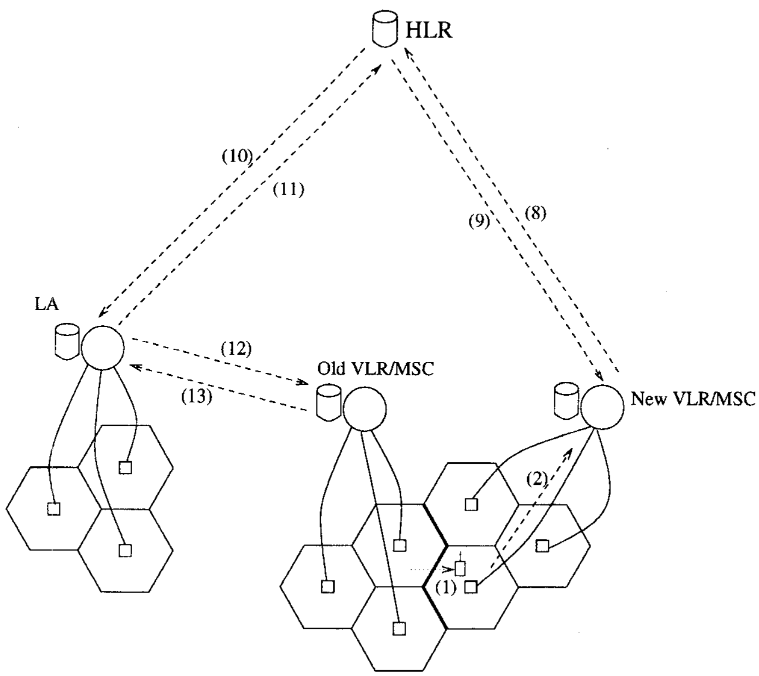

Fig. 6. Reporting location change to the HLR.

the mobility rate and when the cost for accessing the HLR is relatively low. We will describe in more detail these situations in Section IV. The DL scheme is studied in Section V. It is demonstrated that dynamic local anchoring can always achieve lower or equal signaling cost as compared to that of the IS-41 scheme.

Based on local anchoring, the procedure for location registration given in Section II is modified as follows (see Fig. 5 for steps 1–7 and Fig. 6 for steps 8–14).

1) The mobile terminal moves into a new RA and sends a location update message to the nearby base station.
2) The base station forwards this message to the new MSC which updates its associated VLR indicating that the mobile terminal is now residing in its associated area. The new MSC then determines whether it should report the location change to the HLR or to the LA (note that for the SL scheme described above, the location change is never reported to the HLR). If the new MSC decides to report to the HLR, then go to step 8. Otherwise, continue to the next step.
3) The new MSC sends a message to inform the old MSC that the mobile terminal has moved out of its associated RA.
4) The old MSC sends an acknowledgment message to the new MSC together with a copy of the subscriber's user profile.
5) The old MSC removes the record of the mobile terminal in its associated VLR and sends a message to inform the LA of the location change.
6) The LA updates its record indicating the new location of the mobile terminal and sends an acknowledgment message to the old MSC.
7) Location registration is complete (do not continue to next step).

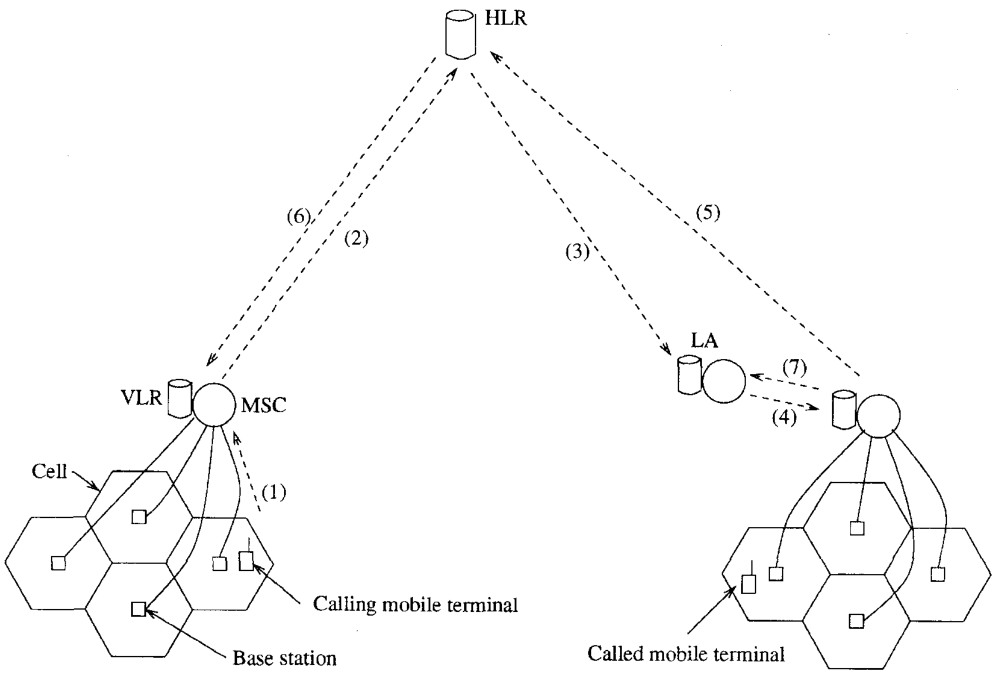

Fig. 7. Modified call delivery.

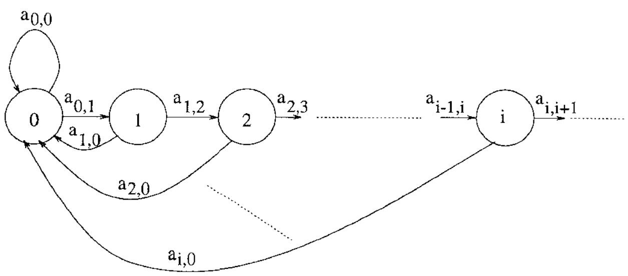

Fig. 8. Imbedded Markov chain model.

8) The new MSC sends a location registration message to the HLR.
9) The HLR sends a registration acknowledgment message to the new MSC together with a copy of the subscriber's user profile.
10) The HLR updates its record indicating the new LA of the mobile terminal and sends a registration cancellation message to the old LA.
11) The old LA removes the record of the mobile terminal and sends a cancellation acknowledgment message to the HLR.
12) The old LA sends a registration cancellation message to the old MSC.
13) The old MSC removes the record of the mobile terminal in its associated VLR and sends a cancellation acknowledgment message to the old LA.
14) Location registration is complete.

The modified call delivery procedure is given as (see Fig. 7).

1) A call is initiated by a mobile terminal which sends a call initiation signal to its serving MSC through the nearby base station.
2) The MSC of the calling mobile terminal sends a location request message to the HLR.
3) The HLR sends a location request message to the LA of the called mobile terminal.
4) The LA forwards the location request message to the MSC serving the called mobile terminal.
5) The called MSC allocates a TLDN to the mobile terminal and sends this TLDN to the HLR. The HLR updates it record such that the current serving VLR of the called mobile terminal becomes the new LA.
6) The HLR forwards the TLDN to the MSC of the calling mobile terminal. The calling MSC can now set up a connection to the called MSC using this TLDN.
7) The serving MSC of the called mobile terminal sends an acknowledgment message to the old LA. The old LA removes its record of the called mobile terminal.

In the above procedures, we assumed that the LA is different from the serving VLR. If they are the same, the messages between the LA and the serving VLR are not necessary and the signaling cost for location registration and call delivery is comparatively lower. Also, note that step 7 of the modified call delivery procedure can take place concurrently with steps 5 and 6 even though they are listed in the above order.

IV. Performance Analysis of Static Local Anchoring

A. Analytical Model for Static Local Anchoring

Let t_c and t_m to be independent and identically distributed (iid) random variables representing the call interarrival time and the RA residence time, respectively. We assume t_c to be exponentially distributed with rate λ_c. We also assume the probability density function of t_m to be $f_m(t)$ with Laplace transform $f_m^*(s)$ and mean $1/\lambda_m$. Fig. 8 shows an imbedded Markov chain model which captures the mobility and call arrival patterns of a mobile terminal. The state of the imbedded Markov chain, i, is defined as the number of RA crossings since the LA was last changed. State transition occurs immediately before the mobile terminal's departure from an RA. Since a movement will occur right after a state transition, the number of movements since the LA was last changed is $i+1$. According to the SL mechanism as described in Section III, a new LA is selected only after a call arrival. As a result, a transition from state i to $i+1$ occurs when there is no call arrival between the $(i+1)$th and the $(i+2)$th movements. Similarly, a transition from state i to zero occurs when at least one call arrives between the $(i+1)$th and the $(i+2)$th movements. The probability that one or more calls arrive between two RA crossings, denoted by ρ, can be obtained as

$$\begin{aligned}\rho &= \int_{t=0}^{\infty}(1-e^{-\lambda_c t})f_m(t)\,dt \\ &= 1 - f_m^*(\lambda_c)\end{aligned} \tag{1}$$

and the state transition probability from state i to state j, denoted by $a_{i,j}$, is

$$a_{i,j} = \begin{cases} 1-\rho, & \text{for } j = i+1 \\ \rho, & \text{for } j = 0 \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

We assume p_i to be the equilibrium state probability of state i. The expression for $p_i (i \geq 0)$ in terms of p_0 is

$$p_i = (1-\rho)^i p_0. \tag{3}$$

Using the law of total probability, the equilibrium state probability of state 0 is obtained as

$$p_0 = \rho. \tag{4}$$

The location tracking cost is divided into two components.

1) Movement Cost: A movement cost is the cost incurred in completing the modified location registration procedure given in Section III. This includes the cost for reporting the mobile terminal's new location to the old VLR and to the LA.

2) Searching Cost: A searching cost is the cost incurred in completing the modified call delivery procedure given in Section III. This includes the cost for locating the mobile terminal and deregistering the mobile terminal from the previous LA.

Similar to [3], we assume that there is a cost associated with each element of the network as shown in Fig. 2 such that the following notations apply:

- C_h Cost for a query or an update of the HLR.
- C_v Cost for a query or an update of the VLR.
- C_l Cost for routing a message by the LSTP.
- C_r Cost for routing a message by the RSTP.
- C_{la} Cost for sending a signaling message through the local A-link.
- C_{ra} Cost for sending a signaling message through the remote A-link.
- C_d Cost for sending a signaling message through the D-link.

The above cost parameters can be expressed in terms of the delay required by the particular network element to process the signaling message. For example, C_h and C_v may represent the delay required to process a query or an update requested by the signaling message; C_l and C_r may represent the delay required to route the signaling message to the appropriate outgoing link; C_{la}, C_{ra}, and C_d may represent the delay for sending the signaling message through the particular link. Other measurements for these cost parameters are possible. For example, the network administration can assign relative costs to the elements of the network based on the current usage and the expenses required to operate the particular network element. When a dynamic location tracking scheme is used (such as the dynamic local anchoring scheme to be discussed in Section V), a high associated cost discourages the usage of the particular network element and thus results in lower overall operating cost for the PCN. In this paper, we do not intend to introduce a method for determining these cost parameters. Instead, we perform the analysis of the proposed location tracking scheme assuming that the above cost parameters are available.

Location registration and call delivery generally involves the transmission of signaling messages from one MSC to another MSC. Here we identify three signaling message paths between two MSC's and we express the cost for sending a signaling message along these paths in terms of the cost parameters as described above.

1) Sending a signaling message from one MSC to another MSC through the HLR (this means that an HLR query or update is necessary): we denote the cost for sending a signaling message along this path by h_1, where

$$h_1 = C_h + C_v + 2C_r + 2C_l + 2C_{ra} + 2C_d + 2C_{la}. \tag{5}$$

2) Sending a signaling message from one MSC to another MSC through the LSTP: we denote the cost for sending a signaling message along this path by h_2, where

$$h_2 = C_v + C_l + 2C_{la}. \tag{6}$$

3) Sending a signaling message from one MSC to another MSC through the RSTP: we denote the cost for sending a signaling message along this path by h_3, where

$$h_3 = C_v + C_r + 2C_l + 2C_d + 2C_{la}. \tag{7}$$

For the expressions given above, we assume a VLR query or update is necessary at either the source or the destination MSC. This results in a C_v term in each of the above expressions. In this paper, we perform the analysis of the proposed location tracking scheme in terms of these three signaling path cost parameters. Several sets of values for h_1, h_2, and h_3 are considered in the performance analysis given in this paper.

The location of each mobile terminal belongs to one of the following three types:

- HOME: The mobile terminal is located at the LA (RA 1 in Fig. 9).
- LOCAL: The mobile terminal is located at an RA other than the LA in the anchor LSTP region (such as RA 2 in Fig. 9).

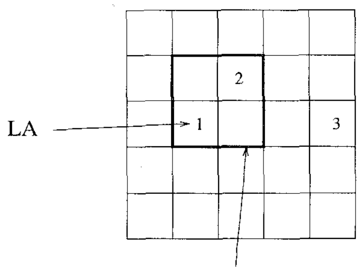

Fig. 9. Registration areas.

TABLE I
COST FOR SEARCHING THE MOBILE TERMINAL WHEN A CALL ARRIVES

Location	Cost
HOME	$s_h = 2h_1$
LOCAL	$s_l = 2h_1 + 2h_2$
REMOTE	$s_r = 2h_1 + 2h_3$

REMOTE: The mobile terminal is outside of the anchor LSTP region (such as RA 3 in Fig. 9).

According to the modified call delivery procedure given in Section III, Table I gives the searching costs for each of the location types: HOME, LOCAL, and REMOTE. Here we assume that the calling and the called mobile terminals are residing in different RA's. If they are in the same RA, no HLR query is necessary for both the local anchoring mechanism and the IS-41 scheme and the searching cost is the same under both schemes. In order to determine the movement cost, we have to know the location of the mobile terminal both before and after the movement. Assuming that the mobile terminal has performed n movements since the LA was last changed, Table II shows the nine possible combinations of the location types when an additional movement, the $(n+1)$th movement, is performed. Based on the modified location registration procedure given in Section III, the last column of Table II gives the movement costs for each of the nine location types A1 to A9.

We assume that RA's are square shaped and there are $d \times d$ RA's arranged in a square in each LSTP region. When a mobile terminal leaves an RA, there is an equal probability that any one of the four neighboring RA's is selected as the destination. We assume $q_h(n), q_l(n)$, and $q_r(n)$ to be the probability that the mobile terminal is located at HOME, LOCAL, and REMOTE, respectively, n movements after the LA was changed. We also assume $r_i(n+1)$ to be the probability that the nth and the $(n+1)$th movements after the LA was changed belong to combination Ai $(1 \le i \le 9)$ as given in Table II. The derivations of $q_h(n), q_l(n)$, and $q_r(n)$ are given in Appendix A and the derivation of $r_j(n)(1 \le j \le 9)$ is given in Appendix B. Let the expected movement and searching costs during the mobile terminal's stay in state i (between the instants that the transition into and the transition out of state i occur) of the imbedded Markov chain be $c_m(i)$ and $c_s(i)$, respectively. The expression for $c_m(i)$ is

$$c_m(i) = \sum_{k=1}^{9} r_k(i+1)m_k. \tag{8}$$

The average movement cost per state transition is

$$C'_m = \sum_{k=0}^{\infty} p_k c_m(k) = \rho \sum_{k=0}^{\infty} (1-\rho)^k c_m(k). \tag{9}$$

The average movement cost per unit time is

$$C_m = \lambda_m C'_m. \tag{10}$$

Assuming that v is the average number of call arrivals between two RA crossings, then

$$v = \frac{\lambda_c}{\lambda_m} \tag{11}$$

the expression for $c_s(i)$ can be obtained as

$$c_s(i) = (v-\rho)s_h + \rho[q_h(i+1)s_h + q_l(i+1)s_l + q_r(i+1)s_r]. \tag{12}$$

The average searching cost per state transition is

$$C'_s = \sum_{k=0}^{\infty} p_k c_s(k) = \rho \sum_{k=0}^{\infty} (1-\rho)^k c_s(k). \tag{13}$$

The average searching cost per unit time is

$$C_s = \lambda_m C'_s. \tag{14}$$

The total cost per unit time for the static local anchoring mechanism is

$$C_T = C_s + C_m. \tag{15}$$

B. Analytical Results

For performance analysis, we are interested in finding out the reduction in cost obtained by the SL mechanism as compared to the IS-41 location strategy. Let D_s and D_m be the per unit time searching cost and movement cost, respectively, of the IS-41 scheme. The expressions of D_s and D_m are

$$D_s = 2h_1\lambda_c \tag{16}$$

$$D_m = 2h_1\lambda_m \tag{17}$$

where λ_c is the call arrival rate and $1/\lambda_m$ is the mean RA residence time of the mobile terminal. The total cost per unit time of the IS-41 scheme is

$$D_T = D_s + D_m. \tag{18}$$

For the analytical results given in this section, we assume that the RA residence time, t_m follows the Gamma distribution with mean $1/\lambda_m$ such that

$$f_m^*(s) = \left(\frac{\gamma\lambda_m}{s+\gamma\lambda_m}\right)^\gamma \tag{19}$$

TABLE II
LOCATION STATE FOR THE nth AND THE $(n+1)$th MOVEMENTS AND THE COST FOR REPORTING THE LOCATION CHANGE TO THE LA

Location	After n moves	After $n+1$ moves	Cost
A1	**HOME**	**LOCAL**	$m_1 = 2h_2$
A2	**HOME**	**REMOTE**	$m_2 = 2h_3$
A3	**LOCAL**	**HOME**	$m_3 = 2h_2$
A4	**LOCAL**	**LOCAL**	$m_4 = 4h_2$
A5	**LOCAL**	**REMOTE**	$m_5 = 2h_2 + 2h_3$
A6	**REMOTE**	**HOME**	$m_6 = 2h_3$
A7	**REMOTE**	**LOCAL**	$m_7 = 4h_3$
A8	**REMOTE**	**REMOTE** (same LSTP)	$m_8 = 2h_2 + 2h_3$
A9	**REMOTE**	**REMOTE** (different LSTP)	$m_9 = 4h_3$

where γ is the shaping parameter. The expression of ρ is then

$$\rho = 1 - \left(\frac{\gamma\lambda_m}{\lambda_c + \gamma\lambda_m}\right)^{\gamma}. \tag{20}$$

The gamma distribution encompasses a family of probability distributions. It can be used to model the exponential, the Erlang, and the chi-square distributions by using the appropriate parameter values. The gamma distribution also allows us to approximately model measured data distributions by fine-tuning the parameters. In the following, we will first demonstrate the cost of SL as compared to that of the IS-41 scheme by using a γ value of one (this is equivalent to the exponential distribution). We will then study the effect of the variance of the RA residence time on the performance of SL by using difference γ values.

1) Cost Comparison: In evaluating the cost of SL we set $\gamma = 1$ such that the RA residence time, t_m, follows the exponential distribution. The expression of ρ is

$$\rho = \frac{\lambda_c}{\lambda_c + \lambda_m}. \tag{21}$$

Here we define the call-to-mobility ratio (CMR) as the ratio of the call arrival rate to the mobility rate such that

$$CMR = \frac{\lambda_c}{\lambda_m}. \tag{22}$$

A high CMR indicates that a large number of calls arrives between two consecutive movements and vice versa. In PCN, the subscriber population comprises of a very diverse group of users. For example, a taxi driver may travel a long distance before receiving a call. This results in low CMR. On the other hand, an office worker may stay in the same location for the whole day while receiving a large number of calls. This results in high CMR. Even for a particular subscriber, the CMR may change depending on the time of the day. It is, therefore, difficult to select a particular CMR that can accurately represent the characteristic of all subscribers. In the following analysis, we will consider a wide range of CMR values, from 0.01 to 100, and determine the performance of the proposed location tracking scheme as the CMR varies.

TABLE III
COST PARAMETERS

Set	h_1	h_2	h_3
1	10	1	9
2	10	1	5
3	10	1	2
4	3	1	3
5	3	1	1
6	1	1	1

In order to show the cost reduction produced by SL relative to the IS-41 scheme, we plot the relative costs $C_s/D_s, C_m/D_m$, and $C_T D_T$ in Fig. 10. The size of an LSTP region, $d \times d$, is set to 64[1] and we vary the CMR from 0.01 to 100. We use six sets of values for the cost parameters h_1, h_2, and h_3 as given in Table III. The value of h_2 is normalized to one since it is the lowest among the three cost parameters. Parameter sets 1 to 3 capture the cases when it is significantly more expensive to send a message through the HLR than sending a message through the LSTP. This is true when when the HLR is far away from the MSC and the communication cost is high or when the cost for accessing the HLR is high. Parameter sets 4 to 6 capture the cases when the costs for sending a message through the HLR is relatively low. These data sets represent the situations when the communication cost between the HLR and the MSC is low and the HLR access is inexpensive. Data set 6 represents an extreme situation such that the cost for sending a message between two MSC is constant regardless of the path selected. We expected that SL will perform the worst under this data set as no cost saving can be obtained by reducing the access to the HLR. Even though this data set may not correspond to a realistic situation, it is a worst scenario and it can be used for comparison purpose.

As can be seen in Fig. 10(c), for low CMR the reduction in total cost is very significant when the cost for sending a

[1] It is demonstrated in [3] that the value of d is between seven and eight assuming one LSTP per LATA and each RA corresponds to an SSP.

message through the HLR, h_1 is relatively high (parameter sets 1 to 3). However, when h_1 is relatively low (parameter sets 4 to 6), the total cost of SL can be higher than that of the IS-41 scheme. These results are as expected because SL always tries to reduce the number of messages going through the HLR by increasing the number of local messages (messages between two MSC's without going through the HLR). This method works with the assumption that it is relatively expensive to send a message through the HLR. If this assumption is not true (as in the case of sets 4 to 6), there may not be any saving in total cost. In some cases, the total cost may be even higher than that of the IS-41 scheme (parameter set 6).

It can also be seen from Fig. 10(c) that the total cost increases as the CMR decreases below 0.1 for all the data sets other than data set 5. When the CMR is low, a large number of movements occur before the arrival of a call and there is a high probability that the mobile terminal is residing outside the anchor LSTP region. As a result, signaling messages between the LA and the serving MSC have to go through the RSTP instead of the LSTP, which results in higher movement and searching costs. When the CMR is high, the call arrival rate is high relative to the mobility rate. As the LA is changed after each call arrival, the LA is the same as the serving VLR most of the time. In this situation, SL is similar to the IS-41 scheme and the total cost of SL approaches that of the IS-41 scheme regardless of the cost parameters selected. Fig. 10(a) and (b) shows the searching cost and the movement cost of SL as compared to that of the IS-41 scheme. It can be seen that SL always results in higher searching cost while the movement cost is lower in most cases. A reduction in total cost is obtained when there is a net cost saving. In some cases (sets 4 and 6), both the movement and the searching costs increase, this results in an increase in total location tracking cost.

2) Effect of RA Residence Time Variance on Performance: Here we study the effect of RA residence time variance on the performance of the SL mechanism. The Laplace transform of the gamma density function is given by (19) and the expression for ρ is given by (20). Since the variance of gamma distribution is $1/\gamma\lambda_m^2$, we can adjust the variance by varying the value of γ while fixing the mean RA residence time to $1/\lambda_m$. A small value of γ results in high variance and vice versa. Fig. 11 shows the effect of RA residence time variance on the cost of SL for parameter sets 3 and 6 as given in Table III. Parameter sets 3 and 6 are selected as they produce the lowest and the highest cost, respectively, in the analytical results given in Section IV-B1. We are interested in finding out whether the results will be affected if different RA residence time variances are used.

We consider three values for γ, 0.01, 1, and 100. When $\gamma = 1$, the RA residence time follows the exponential distribution. A γ value of 0.01 results in large variance and the RA residence time may deviate from its average value significantly. In contrast, a γ value of 100 results in low variance, the RA residence time stays close to its mean value most of the time. Fig. 11 demonstrates the results of the analysis. It can be seen that the total cost for SL is only slightly affected by the RA residence time variance. This can be explained as follows.

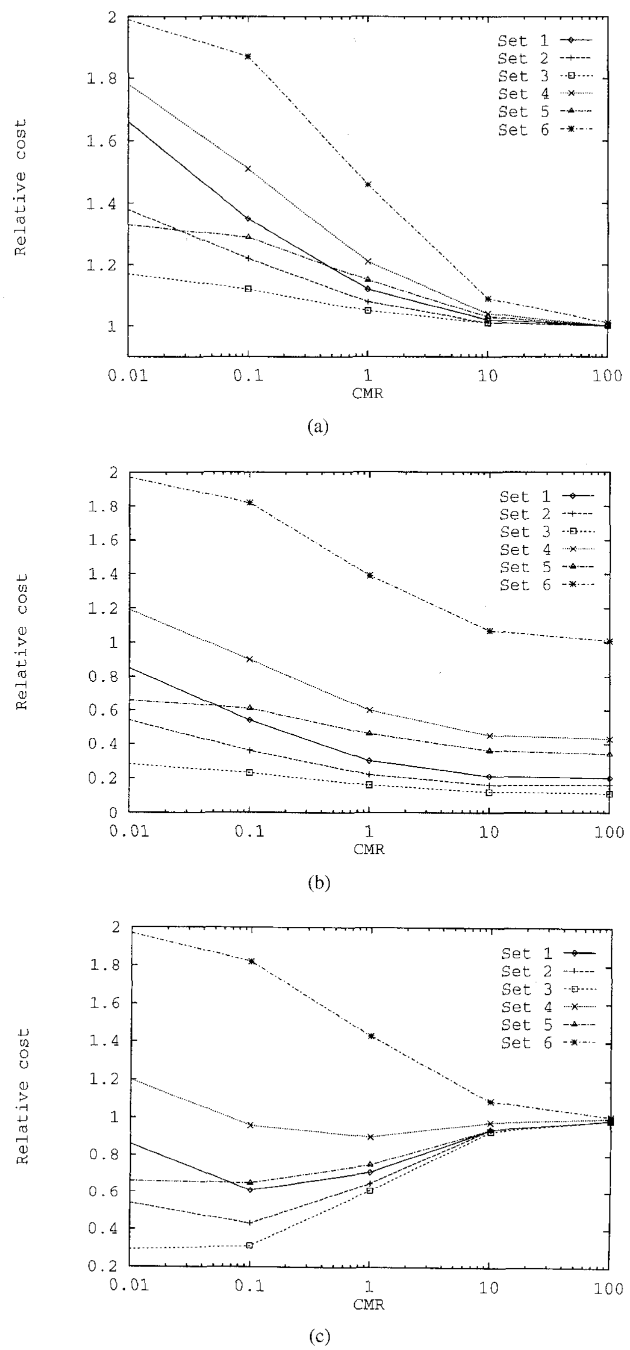

Fig. 10. (a) Searching cost, (b) movement cost, and (c) total cost for SL under exponential RA residence time distribution.

When CMR is high, a large number of call arrivals occur between two movements. The current serving VLR is the same as the LA most of the time regardless of the variance of the RA residence time. In this situation, SL is similar to the IS-41 scheme where the movement cost is independent from the call arrival pattern while the searching cost is independent from the mobility pattern of the mobile terminal. As long as the mobility and call arrival rates are not changed, the total cost for location tracking is not affected.

When the CMR is low, a large number of movements occur between two call arrivals and the LA is rarely changed

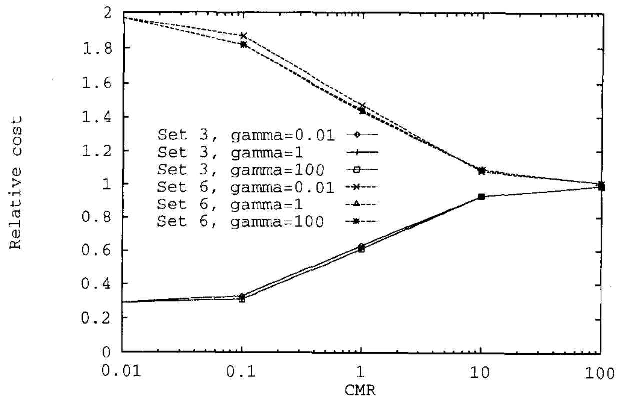

Fig. 11. Total cost for SL under gamma RA residence time distribution.

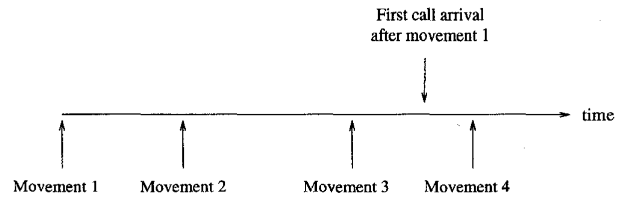

Fig. 12. An example of movement and call arrival events for a mobile terminal.

between two movements. In this situation, the effect of call arrivals on the total cost is small. The total cost is, therefore, approximately equal to the movement cost and is not sensitive to changes in the RA residence time variance.

When the CMR is close to one, the call arrival and the mobility rates are similar. If a mobile terminal stays at a RA for longer than the mean RA residence time, a number of calls may arrive before the next movement. Since the LA is changed whenever a call arrives, the LA is the same as the serving VLR after the first call arrival. Setting up a connection for subsequent call arrivals involves only two VLR queries and thus results in lower total cost. If a mobile terminal stays at an RA for shorter than the average RA residence time, there is a low probability that more than one call will arrive during its stay at the RA. As a result, setting up a connection involves an intermediate LA which results in higher searching cost. Results demonstrated that the increase and the decrease in cost during periods of frequent and infrequent movements, respectively, does not result in a significant net change in the total cost compared to the case when the RA residence time is always close to its mean value. As a result, the total cost is independent from RA residence time variance under all CMR values. The reduction in cost obtained by SL is, therefore, not restricted to the exponential RA residence time distribution. Similar cost saving is achieved under gamma RA residence time distribution with different variances.

Static local anchoring is effective in reducing the cost for location tracking when the cost for accessing the HLR is relatively high. Unless the mobile terminal always stay close to its assigned HLR and the cost for HLR query and update is low, SL should result in an overall reduction in location tracking cost. Two methods can be used to ensure that the location tracking cost under SL will not exceed that of the IS-41 scheme.

1) Given the cost parameters and an estimation of the mobile terminal's CMR, enable SL only if the relative cost, C_T/D_T, is smaller than one. Otherwise, SL should be disabled and the IS-41 location strategy is used.
2) After each movement, the new serving MSC determines whether it should report the location change to the HLR (the IS-41 scheme) or to the LA (the SL scheme). The scheme that results in lower expected location tracking cost is selected.

The first method is straightforward, the network periodically determines the relative location tracking cost for the mobile terminal and enables or disables SL accordingly. In the next section, we will introduce a scheme called dynamic local anchoring (DL) which is based on the second method as described above. It is demonstrated that, in many cases, DL can achieve even lower cost than SL while the total cost of the DL never exceeds that of the IS-41 scheme.

V. Dynamic Local Anchoring

In Section IV-B, we demonstrated that SL can significantly lower the cost of the IS-41 scheme. However, under some situations, the cost of SL exceeds that of the IS-41 scheme and it is more cost effective to report the location changes to the HLR rather than to the LA. Here, we will introduce a scheme that can dynamically determine whether the new MSC should report the new location of the mobile terminal to the HLR or to the LA. Here we define an event to be either a movement of the mobile terminal to another RA or the arrival of an incoming call. Fig. 12 shows the time instants when several events of a particular mobile terminal occur. Assuming that the mobile terminal has just completed movement 1. Movements 2, 3, and 4 as well as the first call arrival after movement 1, as shown in Fig. 12, represent future events. After movement 1, the new serving MSC has two options.

1) Inform the previous VLR of the location change. The previous VLR will update the LA with the new location information of the mobile terminal. This option corresponds to the SL scheme as described in the previous section.
2) Report the new location of the mobile terminal to the HLR and select the new serving VLR as the LA. The HLR will deregister the mobile terminal from its previous LA and VLR. This option corresponds to the IS-41 scheme.

Depending on the CMR of the particular mobile terminal, a number of movements may occur between a given movement and the next call arrival. Given that the mobile terminal has just completed a movement, our objective is to determine the expected cost for all movements before the next call arrival (including the current movement) plus the expected searching cost for the next call under both location registration options as described above. The option that results in the lower expected cost is selected. After the first call arrival, the HLR knows the current serving VLR of the mobile terminal and the LA is the same as the serving VLR regardless of the location registration option selected. The expected cost for subsequent movements and call arrivals is the same under both options. It is, therefore, sufficient to consider only the cost incurred up to and including the first call arrival.

Given that i consecutive movements have occurred, we denote the probability that the next event is a call arrival by ρ_i. We assume that M_1 is the cost for the current movement and M_2 is the cost for the next movement, and so on. We also assume that S_i is the cost for the first call arrival after the current movement given that i movements (including the current movement) have occurred. The expected cost for the movements plus that of the first call arrival, denoted by E, is

$$\begin{aligned} E &= M_1 + \rho_1 S_1 + (1-\rho_1)\{M_2 + \rho_2 S_2 \\ &\quad + (1-\rho_2)[M_3 + \cdots]\} \\ &= M_1 + \rho_1 S_1 + (1-\rho_1) M_2 + (1-\rho_1)\rho_2 S_2 \\ &\quad + (1-\rho_1)(1-\rho_2) M_3 + \cdots . \end{aligned} \tag{23}$$

The values of ρ_i, S_i, and $M_i, i \geq 1$, depend on the location type of the mobile terminal after the current movement as well as the movement and call arrival pattern of the mobile terminal. Determining these parameters may require knowledge of the characteristic of the mobile terminal and it may involve significant computation overhead. To allow the application of this scheme on a dynamic real-time basis, we simplify the computation by considering only the first event after the current movement. We call this the one-step approximation. Based on this approximation, only the first three terms of (23) is used for calculating the expected cost E.

We assume ρ to be the probability that the next event after a given movement is a call arrival. Given that the mobile terminal has just performed a movement, we define a number of additional cost parameters as follows.

- $M_{1,H}$ Cost for registering the mobile terminal at the HLR (this includes the cost for deregistering the mobile terminal at its previous LA and VLR).
- $M_{1,L}$ Costs for registering the mobile terminal at the LA.
- $S_{1,H}$ Cost for searching the mobile terminal if a call arrives before the next movement and registration at the HLR was performed.
- $S_{1,L}$ Cost for searching the mobile terminal if a call arrives before the next movement and registration at the LA was performed.
- $M_{2,H}$ Cost for the next movement if no call arrives before the next movement and registration at the HLR was performed.
- $M_{2,L}$ Cost for the next movement if no call arrives before the next movement and registration at the LA was performed.

The expected cost for the current movement and the first event after the movement if registration at the HLR was performed, denoted by E_H, is

$$E_H = M_{1,H} + \rho S_{1,H} + (1-\rho) M_{2,H}. \tag{24}$$

TABLE IV
EXPRESSIONS FOR $M_{1,H}$ AND $M_{2,L}$ FOR DIFFERENT LOCATION TYPES AFTER THE CURRENT MOVEMENT

Location type after the current movement	$M_{1,H}$	$M_{2,L}$
A1	$2h_1$	$4h_2$
A2	$2h_1$	$2h_2 + 2h_3$
A3	$2h_2$	$2h_2$
A4	$2h_1 + 2h_2$	$4h_2$
A5	$2h_1 + 2h_2$	$2h_2 + 2h_3$
A6	$2h_3$	$2h_2$
A7	$2h_1 + 2h_3$	$4h_2$
A8	$2h_1 + 2h_3$	$2h_2 + 2h_3$
A9	$2h_1 + 2h_3$	$2h_2 + 2h_3$

Similarly, the expected cost for the movement and the first call after the movement if registration at the LA was performed, denoted by E_L, is

$$E_L = M_{1,L} + \rho S_{1,L} + (1-\rho) M_{2,L}. \tag{25}$$

The procedures for location registration and call delivery are given in Section III. During step 2 of the modified location registration procedure, the new MSC of the mobile terminal determines the values of E_H and E_L according to (24) and (25), respectively. If $E_H \leq E_L$, then the new MSC will report the location change to the HLR, otherwise it will report the location change to the LA.

Depending on the current location type of the mobile terminal, the costs $M_{1,L}$ and $S_{1,L}$ can be obtained as given in Tables II and I, respectively. The searching cost $S_{1,H}$ is equal to s_h (given in Table I) since the serving VLR is the same as the LA. Based on the modified location registration procedure, the cost $M_{1,H}$ for each location type is given in Table IV. Determining the cost for the next movement requires knowledge about the type of the next movement and the location registration option selected for that movement. Here we assume that, during the next movement, the mobile terminal will move to an RA, other than anchor RA, belonging to the the same LSTP region and the new MSC will report the location change to the LA. Under these assumptions, the movement cost $M_{2,H}$ is equal to $2h_2$. Table IV also gives the expression for $M_{2,L}$ for each location type after the completion of the current movement.

As described above, the expected location tracking cost is estimated using simple equations. This limits the computation overhead introduced by DL. Nevertheless, a number of optimizations to DL is still possible. For example, if both the pervious and the current movements of the mobile terminal belong to the same type (e.g., location type A4 as given in Table II), all the cost parameters should remain the same and the MSC can reuse the local registration decision from the previous movement. Under this scheme, the MSC only has to make a location registration decision when the mobile terminal moves to another LSTP region or when the mobile move into or away from its LA. In another example, the HLR of the mobile terminal can determine the location registration decision for each movement type A1 through A9, as given in Table II, based on the currently available cost parameters. This information is stored in a table in the mobile terminal's user profile and the MSC can make the location registration decision by simply looking up this table. The HLR will update this table when the mobile terminal moves to another location such that there is a significant change in the values of the cost parameters. Depending on the mobility rate of the mobile terminal, these optimizations can significantly reduce the computation requirement of DL.

For Poisson call arrival and exponential RA residence time, ρ is given by (21). For on-line application of DL, the value of ρ can be estimated by one of the following methods.

1) The VLR collects statistics about the number of times one or more call arrivals occur between two movements and the number of movements performed for a specified time interval. This information is stored in the user profile and can be used to calculate ρ when it is needed.
2) The HLR calculates the value of ρ according to long term call arrival and movement statistics. This information is sent to the serving VLR of the mobile terminal together with the user profile.
3) The system estimates the overall value of ρ for the whole user population. The same ρ value is used for all mobile terminals. Even though this scheme may not be optimal for each particular user, it can obtain overall cost saving when the user population is sufficiently large.

Collecting the mobility and the call arrival statistics of a user can be achieved simply by incrementing the counters stored at the user's profile when a movement or a call arrival occurs. As a result, estimating the value of ρ should not pose a significant overhead to the network.

We will conduct simulations to determine the cost effectiveness of DL under the same assumptions as described in Section IV-BU. Here we assume RA residence time to be exponentially distributed and Fig. 13 gives the results of the simulations using the cost parameter sets given in Table III. It is demonstrated in Fig. 13(c) that the total cost of DL never exceeds that of the IS-41 scheme. As compared to the costs of SL, DL obtains lower total cost for parameter sets 1, 2, 4, and 6. The improvements to parameter sets 1, 2, and 4 are due to limiting the use of local anchoring only when the expected costs can be lowered. Note that the curves for parameter sets 1 and 2 overlap each other for all CMR values. Under these two parameter sets, location changes are reported to the HLR when the mobile terminal moves to another LSTP region. As a result, no signaling messages are transmitted through the RSTP and the difference in the values of h_3 does not affect the movement and searching costs. The performance of DL under parameter sets 1 and 2 is, therefore, the same. For parameter set 6, local anchoring is virtually disabled because it is always more cost effective to register at the HLR. The cost is therefore the same as that obtained by the IS-41 scheme. As compared to SL where the total cost increases as the CMR decreases below 0.1, the total cost under DL decreases as the CMR decreases under all CMR values. The is achieved by the ability of DL to disable local anchoring during inter-LSTP movements[2] when the cost for sending a message through the RSTP is relatively high. This reduces the cost for subsequent movements and call arrivals and thus lowers the total cost.

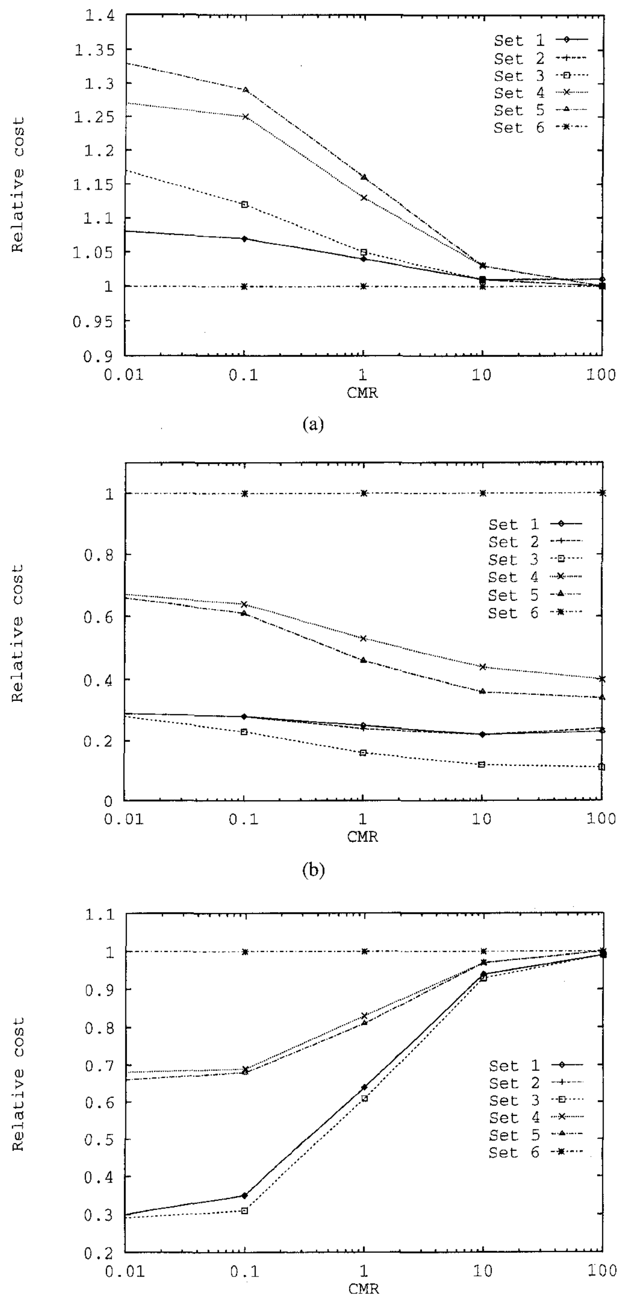

Fig. 13. (a) Searching cost, (b) movement cost, and (c) total cost for the dynamic local anchoring scheme.

Fig. 13(a) and (b) gives the movement and searching costs for DL as compared to that of the IS-41 scheme. It is demonstrated that DL always results in higher searching cost and lower movement cost. The searching cost is higher as in

[2] An inter-LSTP movement occurs when the mobile terminal moves from one LSTP region to another LSTP region.

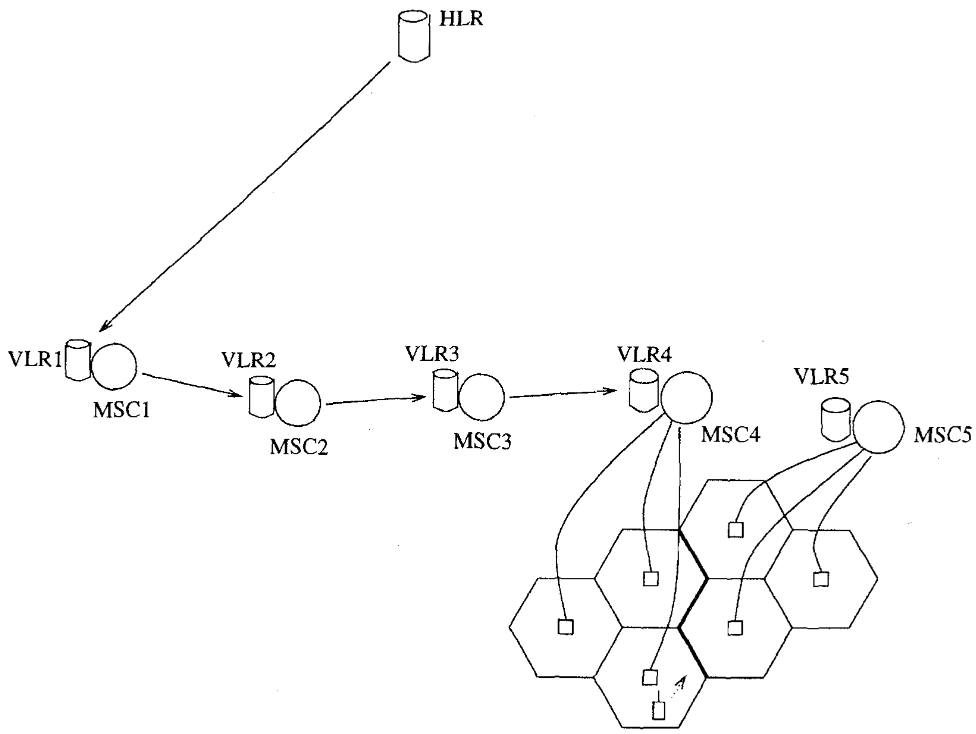

Fig. 14. Location forwarding.

most cases an additional VLR query is necessary to locate the mobile terminal. The movement cost is lower because the number of location registration at the HLR is greatly reduced.

VI. Comparison with Location Forwarding

In this section we compare the proposed local anchoring mechanism with the location forwarding strategy (LF) as introduced in [3]. These two schemes are similar in the sense that both intend to reduce location registration overhead by employing forwarding pointers from one VLR to another VLR. However, with LF, pointer chains are formed which involve a number of VLR's. In order to locate a mobile terminal, the network must transverse the pointer chain which involves the querying of a number of VLR's and introduces additional delay to the connection setup process.

Fig. 14 shows the operation of location forwarding. Assume that VLR 1 was the serving VLR of the mobile terminal when its last call arrived and VLR 4 is the current serving VLR. Under LF, a pointer is set up from the old VLR to the new VLR after each movement. As a result, a pointer chain connecting VLR 1 through VLR 4 exists. When the next call arrives, the HLR first queries VLR 1 and then follows the pointer chain to the current location of the mobile terminal. Because of maximum connection set up delay requirement, the MSC reports the location to the HLR when the pointer chain exceeds a predefined length. Assume that the maximum allowable chain length, denoted by K, is three. When the mobile terminal moves to the RA associated with VLR 5, the new MSC will register the mobile terminal at the HLR and the HLR will deregister the mobile terminal at the previous VLR. Based on the location forwarding scheme as described in [3], old pointer chains are not explicited removed. In order to release the memory consumed by the obsolete pointers, in the following analysis, we assume that the pointer chain is deleted after the location information is reported to the HLR or after a call delivery. A variation of LF which assumes explicit removal of old pointer chains is introduced in [5].

Here we will compare the performance of local anchoring with pointer forwarding under different maximum allowable chain length K. The cost for LF is determined by simulation based on the same cost model as described in Section IV-A. Figs. 15 and 16 show the costs for DL, SL, and LF relative to that of the IS-41 scheme when data sets 2 and 4, respectively, as given in Table III, are used. Figs. 15(c) and 16(c) demonstrate that DL always results in the lowest total cost as compared to other schemes while the total cost for SL is lower than or close to that of LF when the CMR is larger than 0.1. It can be seen that the total cost for LF decreases as the maximum allowable chain length, K, increases. This cost reduction is achieved by reducing the number of accesses to the HLR for location registration. However, increasing K results in longer connection set up delay as more VLR's have to be queried to locate a called mobile terminal. This is undesirable as the call set up delay is a very important QoS parameter for wireless services. However, even when the maximum chain length is set to 4, the signal cost for LF is still higher than that of DL especially when the CMR is small.

Figs. 15(a) and 16(a) show the signaling cost for connection set up relative to that of the IS-41 scheme. The

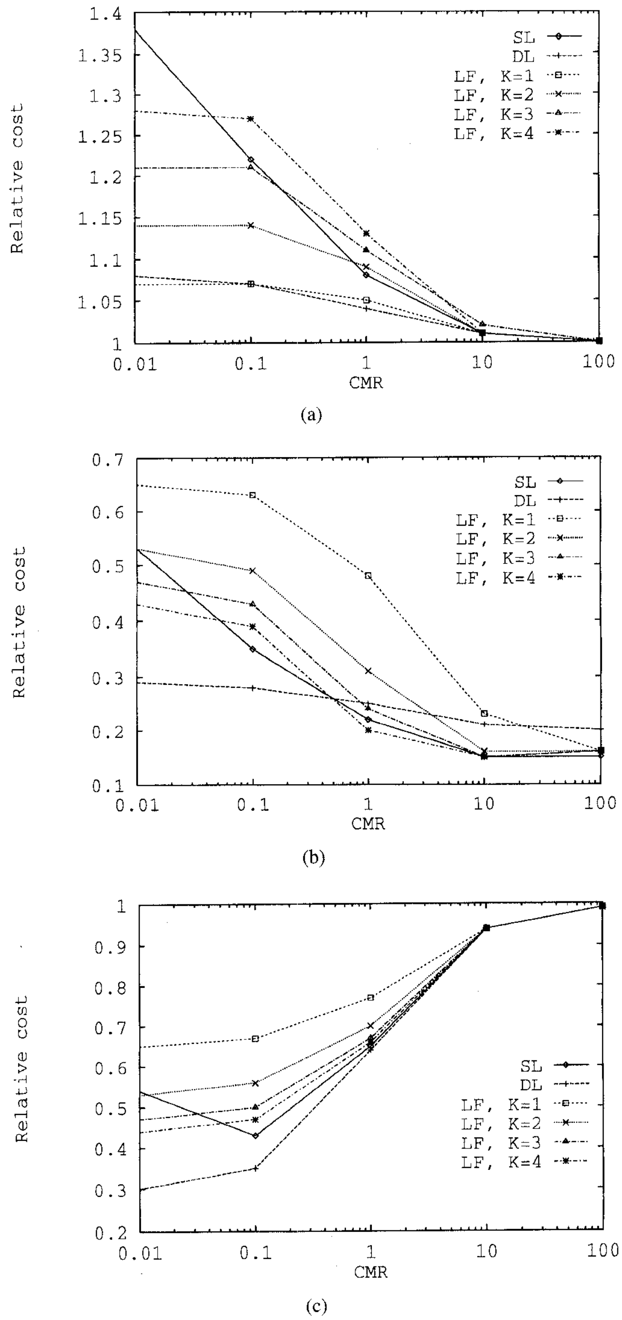

Fig. 15. (a) Searching cost, (b) movement cost, and (c) total cost for DL, SL, and LF under data sets 2.

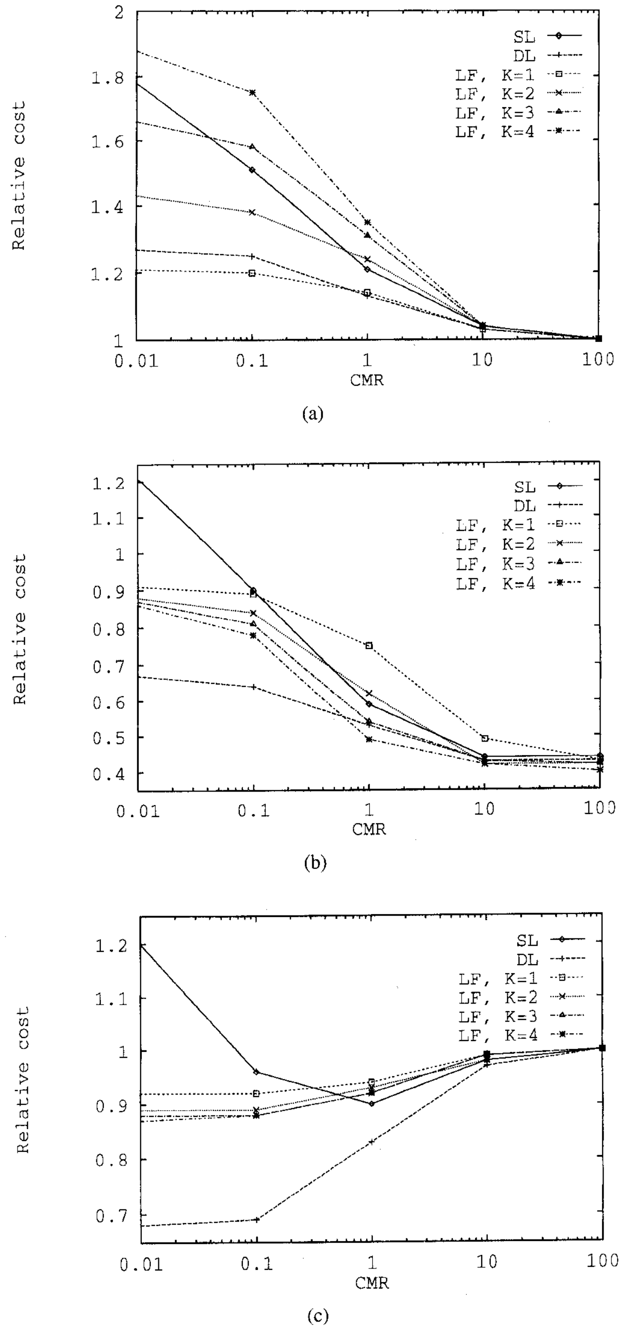

Fig. 16. (a) Searching cost, (b) movement cost, and (c) total cost for DL, SL, and LF under data sets 4.

searching cost for LF is similar to that of DL when the maximum chain length is one. As K increases, the searching cost for LF increases because more VLR queries are required to locate a mobile terminal. The searching costs for SL as well as LF go up significantly when the CMR decreases. This is due to the increased distance between the anchor VLR and the serving VLR. In most cases, setting up a connection requires the transmission of signaling messages through the RSTP which results in higher searching cost.

Figs. 15(b) and 16(b) show the signaling cost for location registration relative to that of the IS-41 scheme. The DL scheme produces significant reduction in movement cost under all CMR values. Both the SL and the LF schemes result in higher movement cost as the CMR decreases. Again, this is due to the increased distance between the anchor VLR and the serving VLR. In most cases, locating a mobile terminal requires the transmission of signaling messages through the RSTP which results in higher movement cost. The LF scheme produces similar or lower movement cost as compared to SL. The cost saving is higher when the maximum chain length is increased.

VII. Conclusion

In this paper, we introduced a location tracking scheme called local anchoring. The primary idea is to replace the relatively expensive location registration messages between the serving MSC and the HLR by messages between nearby MSC's. Two versions of local anchoring are introduced in this paper: static and dynamic local anchoring. Static local anchoring completely removes the need to report location changes to the HLR. When a mobile terminal crosses an RA boundary, the new location is reported to a nearby VLR called the local anchor. Analytical results demonstrated that, in most cases, the cost of static local anchoring is much lower than that of the IS-41 scheme. However, when it is not expensive to access the HLR, static local anchoring may not be cost effective. Dynamic local anchoring improves its static counterpart by making sure that the cost for local anchoring is always lower than that of the IS-41 scheme. Whenever the mobile terminal moves into a new RA, the new serving MSC determines whether it should report the location change to the HLR or to the LA. Based on the call arrival and mobility rate of the mobile terminal, the scheme that incurs the lower cost is selected. Our results demonstrate that the cost for dynamic local anchoring is always lower than or equal to the cost of the IS-41 scheme. In many cases, the dynamic local anchoring improves upon the performance of the static scheme. We also compared local anchoring with Location forwarding as introduced in [3]. Simulation results demonstrated that local anchoring can achieve a lower total location tracking cost while keeping the connection set up delay small.

We have to note that apart from the two local anchoring schemes presented in this paper, other choices for the local anchor are possible. One possibility is a fixed local anchoring scheme such that a selected VLR within the LSTP region will serve as the LA for all mobile terminals within the LSTP region. This may result in increased load to the selected LA and careful design is needed to avoid bottleneck situations. However, as long as sufficient resources are given to the selected VLR (such as computation power and memory space), this scheme may generate better performance than the two schemes described in this paper.

Appendix A
Derivation of the Probabilities $q_h(n), q_l(n)$, and $q_r(n)$

We derive the probabilities that a mobile terminal's location belongs to HOME, LOCAL, and REMOTE, respectively, n movements after the LA were changed. Let $\alpha_{i,j}(n)$ be the probability that a mobile terminal originating at RA i moves to RA j after n RA crossings. Let x and y be the distance between the two RA's along the x and the y directions such that

$$x = x_i - x_j \tag{26}$$

$$y = y_i - y_j \tag{27}$$

where (x_i, y_i) and (x_j, y_j) are the coordinates for RA's i and j, respectively. For a two-dimensional (2-D) PCN coverage area with square-shaped RA's as shown in Fig. 9, a mobile terminal can move in four directions: LEFT, RIGHT, UP, and DOWN. We assume $r(0 \le r \le n)$ to be the number of RIGHT movement performed. Given that the total number of movements is n, the number of LEFT, UP, and DOWN movements can be expressed in terms of r, x, and y. We denote the number of LEFT, UP, and DOWN movements by $l(r,x,y), u(r,x,y)$, and $d(r,x,y)$, respectively, and their expressions are given as

$$l(r,x,y) = r + x \tag{28}$$

$$u(r,x,y) = \tfrac{1}{2}(n - 2r - x - y) \tag{29}$$

$$d(r,x,y) = \tfrac{1}{2}(n - 2r - x + y). \tag{30}$$

The number of possible paths from RA i to RA j when exactly n movements are performed is

$$f(n,x,y) = \sum_{r=0}^{n} g(r,x,y) \tag{31}$$

where $g(r,x,y)$ is defined as follows below.

If all of $r, l(r,x,y), u(r,x,y)$, and $d(r,x,y)$ are positive integers, then

$$g(r,x,y) = \frac{n!}{r!\,l(r,x,y)!\,u(r,x,y)!\,d(r,x,y)!} \tag{32}$$

otherwise, $g(r,x,y)$ is equal to zero.

The probability $\alpha_{i,j}(n)$ is given as

$$\alpha_{i,j}(n) = \frac{f(n,x,y)}{4^n}. \tag{33}$$

Here, the numerator represents the number of possible paths from RA i to RA j in exactly n movements. The denominator represents the number of possible path that the mobile terminal can travel in n movements when the destination is not specified.

The probability $q_h(n)$ is the same as the probability that a mobile terminal originating at an RA (the LA) and returns to the same RA after n movements. The expression for $q_h(n)$ is

$$q_h(n) = \frac{f(n,0,0)}{4^n}. \tag{34}$$

We assume that R is the set of all RA's in the anchor LSTP region. The expression for the probability $q_l(n)$ is

$$q_l(n) = \frac{1}{d^2} \sum_{i \in R} \sum_{j \in R, j \ne i} \alpha_{i,j}(n). \tag{35}$$

The probability $q_r(n)$ is

$$q_r(n) = 1 - q_h(n) - q_l(n). \tag{36}$$

Appendix B
Derivation of the Probability $r_i(n)$

Here we derive the probabilities that the $(n-1)$th and the (n)th movements belong to location types A1 through A9. We partition the each LSTP region and its surrounding RA's according to Fig. 17. We assume that π_A and π_B are the probabilities that a mobile terminal is located at partition A and partition B in any LSTP region, respectively. Let the

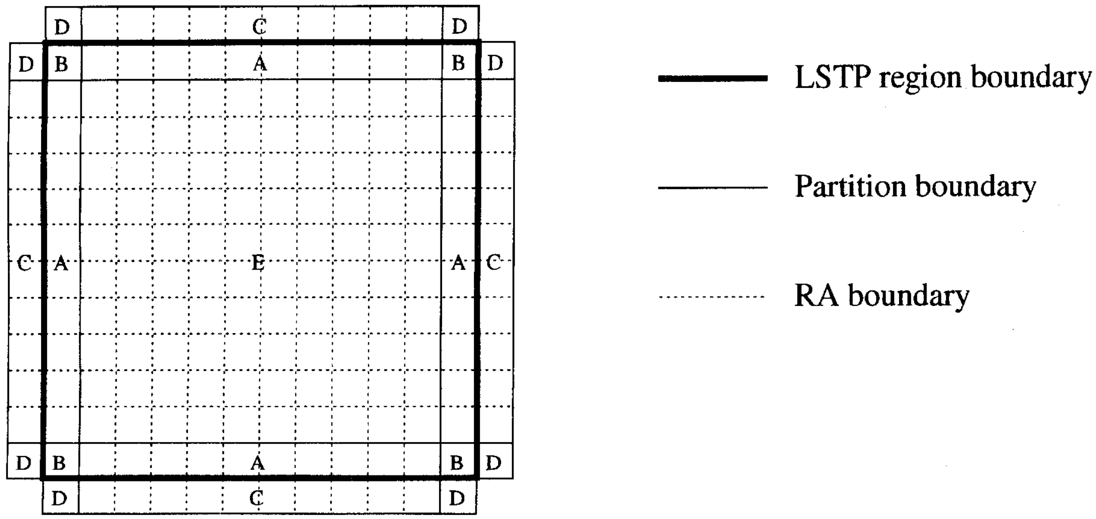

Fig. 17. Partitions of an LSTP region.

size of each LSTP region be $d \times d$, the expressions for π_A and π_B are

$$\pi_A = \frac{4(d-2)}{d^2} \tag{37}$$

$$\pi_B = \frac{4}{d^2}. \tag{38}$$

Let $\sigma(n)$ be the probability that a mobile terminal is at a neighboring RA of the LA n movements after leaving the LA. Let RA i be the LA and N be the set of the four neighbors of the LA. The expression of $\sigma(n)$ is

$$\sigma(n) = \sum_{j \in N} \alpha_{i,j}(n). \tag{39}$$

The derivation of $\alpha_{i,j}(n)$ is given in Appendix A. We also assume that $\beta_z(n)$, where $z \in \{A, B, C, D, E\}$, is the probability that the mobile terminal is located at partition z of the anchor LSTP region (and its outer perimeter) n movements after leaving the LA. The expression for $\beta_z(n)$ is given as

$$\beta_z(n) = \frac{1}{d^2} \sum_{i \in R} \sum_{j \in z} \alpha_{i,j}(n). \tag{40}$$

We assume $\theta = 1 - \pi_a - \pi_b$, the probabilities $r_1(n)$ through $r_9(n)$ can be expressed in terms of $\theta, \pi_A, \pi_B, \sigma(n)$ and $\beta_z(n)$ as

$$r_1(n) = q_h(n-1)[\theta + \tfrac{3}{4}\pi_A + \tfrac{1}{2}\pi_B] \tag{41}$$

$$r_2(n) = q_h(n-1)[\tfrac{1}{4}\pi_A + \tfrac{1}{2}\pi_B] \tag{42}$$

$$r_3(n) = \tfrac{1}{16}\sigma(n-1)[4 - \pi_A - 2\pi_B] \tag{43}$$

$$r_4(n) = q_l(n-1)[\theta + \tfrac{3}{4}\pi_A + \tfrac{1}{2}\pi_B] - r_3(n) \tag{44}$$

$$r_5(n) = q_l(n-1)[\tfrac{1}{4}\pi_A + \tfrac{1}{2}\pi_B] \tag{45}$$

$$r_6(n) = \tfrac{1}{16}\pi_A\sigma(n-1) + \tfrac{1}{8}\pi_B\sigma(n-1) \tag{46}$$

$$r_7(n) = \tfrac{1}{4}[\beta_C(n-1) + \beta_D(n-1)] - r_6(n) \tag{47}$$

$$r_8(n) = \tfrac{3}{4}[\pi_A - \beta_A(n-1)] + \tfrac{1}{2}[\pi_B - \beta_B(n-1)] + [\theta - \beta_E(n-1)] \tag{48}$$

$$r_9(n) = \tfrac{1}{4}[\pi_A - \beta_A(n-1) - \beta_C(n-1)] + \tfrac{1}{2}[\pi_B - \beta_B(n-1) - \beta_D(n-1)] + \tfrac{1}{4}\beta_D(n-1) \tag{49}$$

where $q_h(n)$ and $q_l(n)$ are given in Appendix A.

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