Local Anchor Scheme for Reducing Location Tracking Costs in PCNs

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Abstract

A Personal Communication Network (PCN) location tracking scheme called "local anchoring" is introduced which reduces the signaling cost as compared to the location strategy proposed in the IS-41 standard. Local anchoring minimizes the number of location registration messages between the home location register (HLR) and the visitor location registers (VLRs) 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 is minimized. Experimental results demonstrated that the cost of dynamic local anchoring is always lower than or equal to that of the IS-41 scheme.

Key Words: *Home Location Register, Visitor Location Register, Local Anchoring, Location Registration, Call Delivery.*

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1 Introduction

Personal Communication Networks (PCNs) provide communication services to subscribers that travel within the network coverage area. In order to correctly locate a mobile terminal when an incoming call arrives, a number of methods are proposed to keep track of the up-to-date location of each mobile terminal [4, 7]. Two standards currently exist for PCN mobility management: IS-41 [1, 7] and GSM [7, 8]. The IS-41 is commonly used in North America while the GSM is popular in Europe. Both IS-41 and GSM employ out-of-band signaling such that a dedicated signaling network such as *Signaling System No. 7* (SS7) [6] is used for network administration functions such as location registration and connection establishment. Both of these standards are based on a two-level database hierarchy. Two types of databases, *home location register* (HLR) and *visitor location register* (VLR) are used to store the location information of the mobile terminals. Figure 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* (RAs). All base stations belonging to a giving RA are wired to a *mobile switching center* (MSC). In Figure 1, we assume that the VLR is co-located with the MSC which in turn is connected to the rest of the signaling network through a *local signal transfer point* (LSTP). We call the area covered by all RAs belonging to an LSTP the

LSTP region. Depending on the network configuration, there may exist one or more HLRs in the PCN. Figure 1 assumes a single HLR and it is connected to the signaling network through a *regional signal transfer point* (RSTP). The RSTP and the LSTPs are responsible for routing messages in the SS7 network and the RSTP is connected to all the LSTPs in the region. 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 the VLR which in turn sends a location registration message to the HLR. The HLR will acknowledge the VLR for the successful registration and it will also deregister the mobile terminal at the old VLR. In order to locate a mobile terminal for call delivery, the HLR is queried to determine the serving VLR of the destination mobile terminal. The HLR then sends a message to this VLR which in turn will determine the serving base station of the mobile terminal by paging all cells within its associated RA. This location registration scheme requires the exchange of signaling messages between the HLR and the new and old VLRs whenever the mobile terminal crosses an RA boundary. This may result in significant traffic load to the SS7 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 RAs.

A number of efforts have been reported to reduce the signaling load to the SS7 network. A caching strategy is introduced in [3] which reduces the cost for call delivery by reusing the cached information about a called user's location from a previous call. In [5], a threshold scheme is introduced that dynamically determines the time when a cache record becomes obsolete. In [2], a location forwarding strategy is proposed to reduce the signaling costs for location registration. Whenever a mobile terminal crosses an RA boundary, a pointer is set up from the old VLR to the new VLR. 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 the call to mobility ratio is low. However, a maximum of K 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.

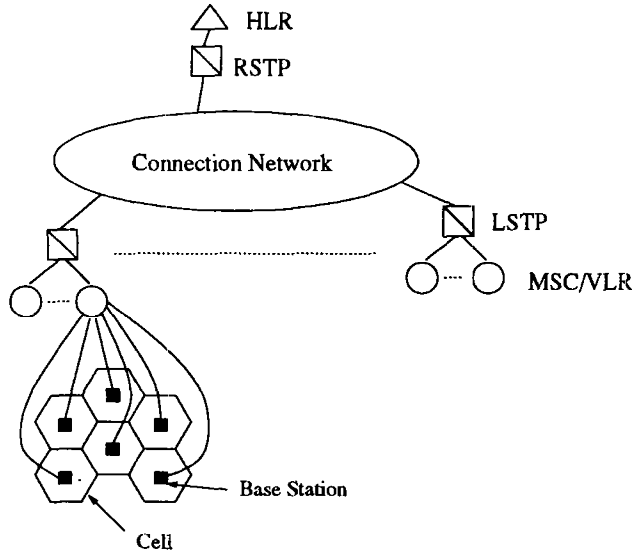

Figure 1: PCN architecture.

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 *local anchor* (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 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. In some cases, as will be described in Section 3, the LA is the same as the serving VLR. Under this situation, the second query is not necessary. Two schemes for selecting the LA are proposed in Section 3. 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 5 a dynamic local anchoring scheme that can dynamically determine whether the mobile terminal should report to the LA or directly to the HLR after each movement. Dynamic local anchoring can achieve a lower expected signaling cost as compared to that of the IS-41 scheme.

This paper is organized as follows. In Section 2 we describe the reference PCN architecture. Section 3 introduces the local anchoring mechanism. An analytical model for local anchoring is given in Sections 4 and the performance of local anchoring is compared to

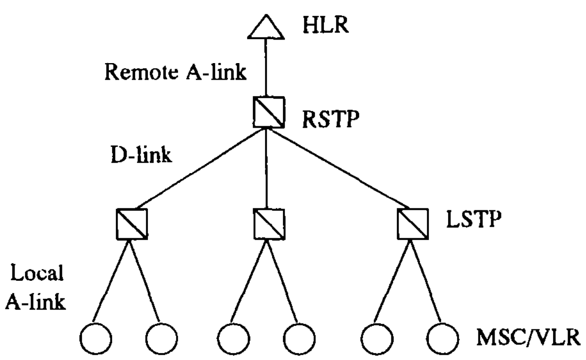

Figure 2: Reference architecture.

that of the IS-41 scheme. Section 5 proposes a scheme for dynamically selecting the anchor VLR and studies the performance of this dynamic scheme. The conclusion is given in Section 6.

2 System Description

The PCN architecture given in Figure 1 assumes that the HLR and the VLRs communicate through a connection network. A message between the HLR and a VLR (or between two VLRs) may go through several intermediate switches inside the connection network before reaching its destination. The cost for transmitting a signaling message between the HLR and different VLRs (and between different pairs of VLRs) may therefore vary. In order to simplify the analysis and the cost model, we will use the simplified PCN architecture as given in Figure 2. Similar architectures are used in [2, 3, 7]. According to Figure 2, there are three types of connections among the network elements. The Remote A-link connects the HLR to the RSTP, the D-links connect the RSTP to the LSTPs and the local A-links connect the LSTPs to their associated MSCs and VLRs. 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 VLRs at different RAs to be the same.

Procedures for location registration and call delivery are proposed in the IS-41 standard [1, 7]. According to the IS-41 location strategy, the HLR always knows exactly the ID of the serving VLR of a mobile terminal. We outline the major steps of the IS-41 location registration scheme as follows (see Figure 3):

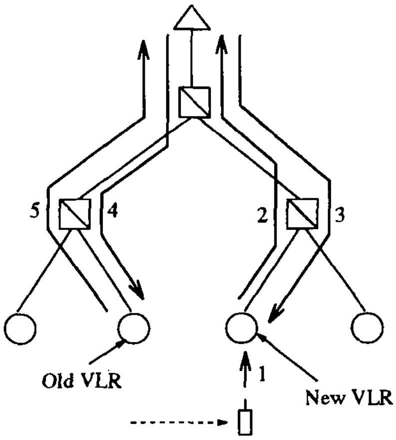

Figure 3: Location registration.

1. The mobile terminal sends a location update message to the new VLR.
2. The new VLR sends a location registration message to the HLR.
3. The HLR sends a registration acknowledgement message to the new VLR.
4. The HLR sends a registration cancellation message to the old VLR.
5. The old VLR sends a cancellation acknowledgement message to the HLR.

and the IS-41 call delivery scheme is outlined as follows (see Figure 4):

1. The VLR of the calling mobile terminal sends a location request message to the HLR.
2. The HLR sends a location request message to the VLR serving the called mobile terminal.
3. The VLR determines the cell location of the called mobile terminal and sends the location information to the HLR.
4. The HLR sends the location information to the VLR of the calling mobile terminal.

The above call delivery procedure assumes that the calling and the called mobile terminals are residing in different RAs. If they are located in that same RA, no HLR query is necessary as the information of the called mobile terminal is available locally.

3 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 described in Section 2, the VLR sends

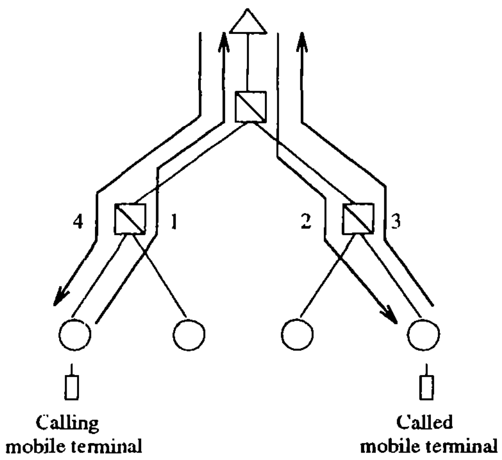

Figure 4: Call delivery.

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 far away from the HLR, excessive amount of location registration messages are transmitted between the serving VLR 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 VLR 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 the HLR, location registration may still generate significant communication load to the SS7 network as well as heavy querying load to the HLR. Here we will introduce a location registration scheme which minimizes the signaling traffic by removing the need to transmit location registration messages to the HLR whenever the mobile terminal crosses an RA boundary. Under our scheme, the VLR of the newly entered RA registers the mobile terminal's location at a nearby VLR. We call this VLR the *local anchor* (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 will be set up in a table at this VLR indicating the current serving VLR for the mobile terminal. The HLR 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 VLRs in each LSTP region. The IS-41 location strategy is a special case of local anchoring which selects a new LA after every call arrival or RA crossing such that the LA is always the same as the serving VLR. In this paper, we introduce two methods for selecting the LA:

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.

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 selects the serving VLR during the last call arrival as the new LA. This is reasonable because the HLR knows the location of 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 4. 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 the mobility rate and when the cost for transmitting a message between the HLR and the VLR is relatively low as compared to transmitting a message between two VLRs. We will describe in more detail these situations in Section 4. The DL scheme is studied in Section 5. It is demonstrated that dynamic local anchoring can always achieve lower (or equal) location tracking cost as compared to that of the IS-41 scheme.

Based on local anchoring, the *procedure for location registration* given in Section 2 is modified as follows (see Figure 5 for steps 1-7 and Figure 6 for steps 8-14):

1. The mobile terminal sends a location update message to the new VLR.
2. The new VLR 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 VLR decides to report to the HLR, then go to step 8. Otherwise, continue to the next step.
3. The new VLR sends a message to inform the previous VLR that the mobile terminal has moved out of its associated RA.

4. The previous VLR sends a message to inform the LA of the location change.

5. The LA updates its record and sends an acknowledgement message to the previous VLR.

6. The previous VLR sends an acknowledgement message to the new VLR.

7. Location registration is complete (do not continue to next step).

8. The new VLR sends a location registration message to the HLR.

9. The HLR sends a registration cancellation message to the LA.

10. The LA sends a registration cancellation message to the old VLR.

11. The old VLR sends a cancellation acknowledgement message to the LA.

12. The LA sends a cancellation acknowledgement message to the HLR.

13. The HLR sends a registration acknowledgement message to the new VLR. The HLR also updates its record such that the new VLR becomes the LA of the mobile terminal.

14. Location registration is complete.

The modified *call delivery procedure* is given as (see Figure 7):

1. The VLR of the calling mobile terminal sends a location request message to the HLR.

2. The HLR sends a locations request message to the LA of the called mobile terminal.

3. The LA sends a locations request message to the VLR serving the called mobile terminal.

4. The VLR determines the cells location of the called mobile terminal and sends the location information to the LA.

5. The LA sends the location information to the HLR.

6. The HLR sends the location information to the VLR of the calling mobile terminal.

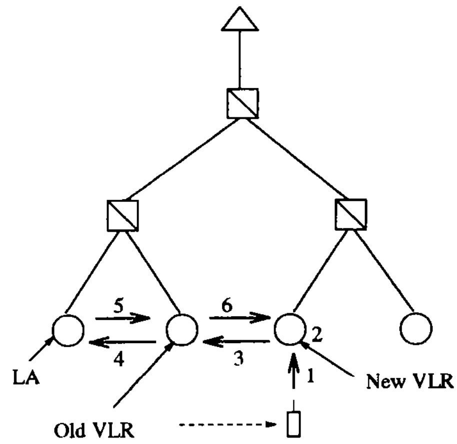

Figure 5: Reporting location change to the LA.

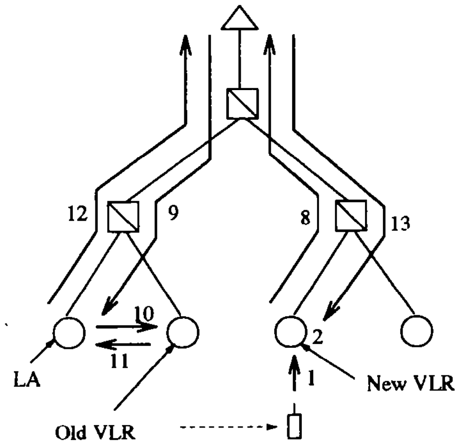

Figure 6: Reporting location change to the HLR.

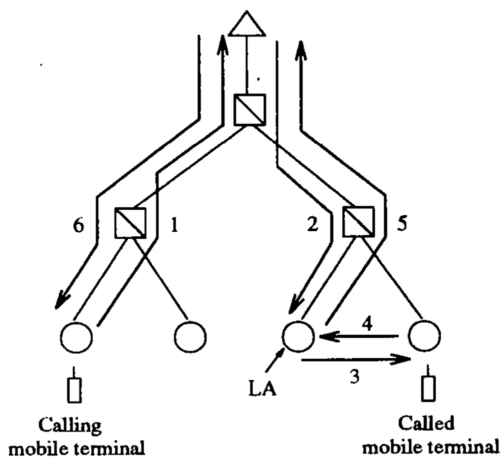

Figure 7: Modified call delivery.

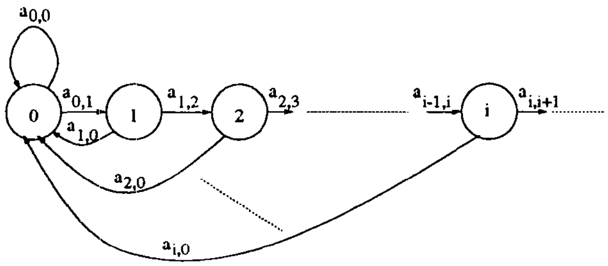

Figure 8: Imbedded Markov chain model.

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 cost for location registration and call delivery will be comparatively lower. A cost model for the location registration and the call delivery procedures is introduced in Section 4.

4 Performance Analysis of Static Local Anchoring

4.1 Analytical Model

Let t_c and t_m to be iid (independent and identically distributed) 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 $1/\lambda_m$. Figure 8 shows an imbedded Markov chain model which captures the mobility and call arrival 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 3, 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 0 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:

$$\rho = \int_{t=0}^{\infty} (1 - e^{-\lambda_c t}) f_m(t) dt \qquad (1)$$

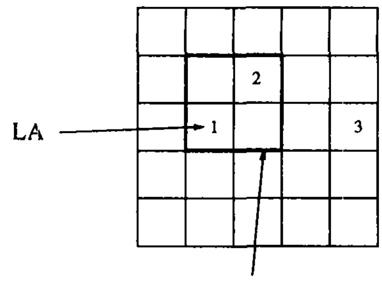

Figure 9: Registration areas.

$$= 1 - f_m^*(\lambda_c) \qquad (2)$$

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

$$a_{i,j} = \begin{cases} 1-\rho & \text{for } j = i+1 \\ \rho & \text{for } j = 0 \\ 0 & \text{otherwise} \end{cases} \qquad (3)$$

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:

$$p_i = (1-\rho)^i p_0 \qquad (4)$$

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

$$p_0 = \rho \qquad (5)$$

The location tracking cost is divided into two components:

Movement Cost: the cost incurred in completing the modified location registration procedure given in Section 3. This includes the cost for reporting the mobile terminal's new location to the old VLR and to the LA.

Searching Cost: the cost incurred in completing the modified call delivery procedure given in Section 3. This includes the cost for locating the mobile terminal and deregistering the mobile terminal from the previous LA.

We define the cost parameters h_1, h_2 and h_3 to be as follows:

h_1 = The cost for sending a message from a VLR to another VLR through the HLR (this means that an HLR query or update is necessary.) The two VLRs are the same when the message from the VLR to the HLR represents a request and the message from the HLR back to the VLR represents an acknowledgement.

Location	Cost
HOME	$s_1 = h_1$
LOCAL	$s_2 = h_1 + 2h_2$
REMOTE	$s_3 = h_1 + 2h_3$

Table 1: Cost for searching the mobile terminal when a call arrives.

h_2 = The cost for sending a message from a VLR to another VLR through the LSTP.

h_3 = The cost for sending a message from a VLR to another VLR through the RSTP.

The above costs include the link cost (A-links and D-links), the switching cost at the LSTP or RSTP, and the databases access cost (HLR and VLR). The costs may be measured in terms of the delay or the amount of processing required. In this paper, we assume that the above cost parameters are given. Several sets of cost parameters 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 Figure 9).

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

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

According to the modified call delivery procedure given in Section 3, Table 1 gives the searching costs for each of the location types: **HOME**, **LOCAL**, **REMOTE**. Here we only include the cost for message exchange between the HLR and the serving VLR of the called mobile terminal. The cost for the message exchange between the calling VLR and the HLR is the same for both the local anchoring mechanism and the IS-41 scheme and is not considered in this paper. Table 1 also assumes that the calling and the called mobile terminals are residing in different RAs. If they are in the same RA, no HLR query is necessary for both the localing 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. Assume that the mobile terminal has performed n movements

Location	After n moves	After $n+1$ moves
A1	**HOME**	**LOCAL**
A2	**HOME**	**REMOTE**
A3	**LOCAL**	**HOME**
A4	**LOCAL**	**LOCAL**
A5	**LOCAL**	**REMOTE**
A6	**REMOTE**	**HOME**
A7	**REMOTE**	**LOCAL**
A8	**REMOTE**	**REMOTE** (same LSTP)
A9	**REMOTE**	**REMOTE** (different LSTP)

Table 2: Location state for the n^{th} and the $(n+1)^{th}$ movements.

since the LA was last changed, Table 2 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 3, Table 3 gives the movement cost for each of the nine location types **A1** to **A9** given in Table 2.

We assume that RAs are square shaped and there are $d \times d$ RAs 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 RAs is selected as the destination. We assume $q_1(n)$, $q_2(n)$ and $q_3(n)$ to be the probabilities 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 n^{th} and the $(n+1)^{th}$ movements after the LA was changed belong to combination **Ai** $(1 \leq i \leq 9)$ as given in Table 2. The derivations of $q_i(n)$ $(1 \leq i \leq 3)$ and $r_j(n)$ $(1 \leq j \leq 9)$ are given in Appendix A and Appendix B, respectively. 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:

$$c_m(i) = \sum_{k=1}^{9} r_k(i+1) m_k \qquad (6)$$

The *average movement cost per state transition* is:

$$C'_m = \sum_{k=0}^{\infty} p_k c_m(k) = \rho \sum_{k=0}^{\infty} (1-\rho)^k c_m(k) \qquad (7)$$

The *average movement cost per unit time* is:

$$C_m = \lambda_m C'_m \qquad (8)$$

Location	Cost
A1	$m_1 = 2h_2$
A2	$m_2 = 2h_3$
A3	$m_3 = 2h_2$
A4	$m_4 = 4h_2$
A5	$m_5 = 2h_2 + 2h_3$
A6	$m_6 = 2h_3$
A7	$m_7 = 4h_3$
A8	$m_8 = 2h_2 + 2h_3$
A9	$m_9 = 4h_3$

Table 3: Cost for reporting the location change to the LA after a movement.

Assume v to be the average number of call arrivals between two RA crossings (the expression of v is given in Section 4.2), the expression for $c_s(i)$ can be obtained as:

$$c_s(i) = (v - \rho)s_1 + \rho \sum_{k=1}^{3} q_k(i+1)s_k \qquad (9)$$

The *average searching cost* per state transition is:

$$C'_s = \sum_{k=0}^{\infty} p_k c_s(k) = \rho \sum_{k=0}^{\infty} (1-\rho)^k c_s(k) \qquad (10)$$

The *average searching cost* per unit time is:

$$C_s = \lambda_m C'_s \qquad (11)$$

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

$$C_T = C_s + C_m \qquad (12)$$

4.2 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:

$$D_s = h_1 \lambda_c \qquad (13)$$

$$D_m = 2h_1 \lambda_m \qquad (14)$$

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

$$D_T = D_s + D_m \qquad (15)$$

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

Table 4: Cost parameters used in experiments.

For the experimental results given in this section, we assume that the RA residence time, t_m, is exponentially distributed such that:

$$\rho = 1 - f_m^*(\lambda_c) = \frac{\lambda_c}{\lambda_c + \lambda_m} \qquad (16)$$

and

$$v = \frac{\lambda_c}{\lambda_m} \qquad (17)$$

In order to show the cost reduction produced by SL relative to the IS-41 scheme, we plot $\frac{C_s}{D_s}$, $\frac{C_m}{D_m}$ and $\frac{C_T}{D_T}$ in Figure 10. The size of an LSTP region[1], $d \times d$, is set to 64 and we vary the call to mobility ratio (CMR), $\frac{\lambda_c}{\lambda_m}$, 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 4. The value of h_2 is normalized to 1 since it is the lowest among the three cost parameters. Parameter sets 1 to 3 capture the cases when it is significantly more expensive sending a message through the HLR than sending a message through the LSTP. Parameter sets 4 to 6 capture the cases when the costs for sending a message through the HLR is relatively low. As can be seen in Figure 10(c), for low CMR the reduction in total cost (the sum of the movement cost and the searching cost) is very significant when the cost for sending a 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 send from VLR to VLR without going through the HLR). This method works with the assumption that it is relatively expansive 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

[1] It is demonstrated in [2] that the value of d is between 7 and 8 assuming one LSTP per LATA and each RA corresponds to an SSP.

cost. In some cases, the total cost may be even higher than that of the IS-41 scheme (parameter set 6). For high CMR, a number of call arrivals may occur during the mobile terminal's stay at an RA. As a result, there is a high probability that the LA is the same as the serving VLR. The the total cost of SL, therefore, approaches that of the IS-41 scheme regardless of the cost parameters selected. Figures 10(a) and (b) show 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 reduction. In some cases (sets 4 and 6), both the movement and the searching costs increase, this results in an increase in total location tracking costs.

Static local anchoring is effective in reducing the cost for mobility tracking when the cost for accessing the HLR is relatively high. Unless the mobile terminal always stays at its home location (such that its distance from the HLR is small) and the cost for HLR query and update is low, SL should result in an overall reduction in location tracking cost. When it is absolutely not desirable to have a total cost higher than that of the IS-41 scheme even in a rare circumstance, another scheme called dynamic local anchoring (DL) can be used. We will introduce DL in the next section which can dynamically determine whether the LA should be changed after each movement such that the expected cost until the next movement is minimized. In many cases, DL can achieve even lower cost than SL. The total cost of the DL never exceeds that of the IS-41 scheme.

5 Dynamic Local Anchoring

In Section 4.2 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 change to the HLR rather than to the LA. Here, we will introduce a scheme that can dynamically determine whether the new VLR should report the location of the mobile terminal to the HLR or to the LA. Figure 11 shows the call arrivals between two movements. After movement 1, the new serving VLR has two options:

1. Report the new location of the mobile terminal to the HLR and select this new VLR as the LA. The HLR will deregister the mobile terminal from its previous LA and VLR.

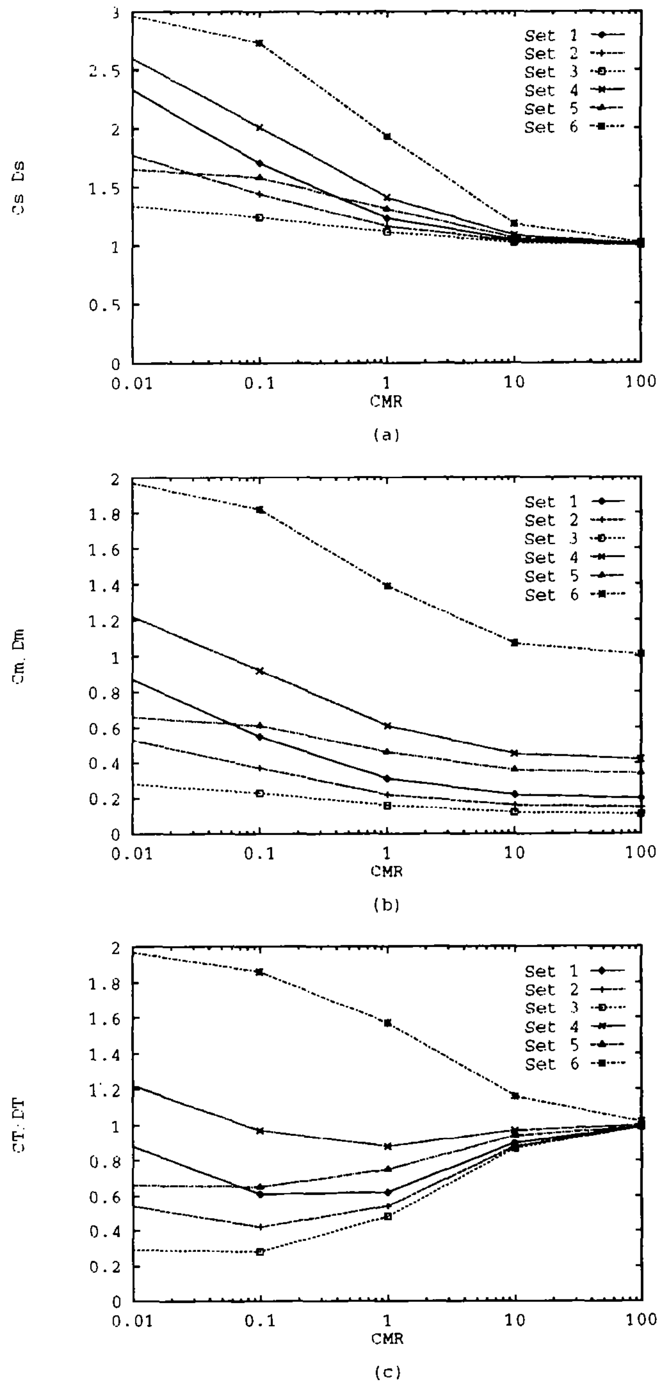

Figure 10: (a) Searching cost (b) Movement cost and (c) Total cost for the static local anchoring scheme (SL).

2. Inform the previous VLR of the location change. The previous VLR will update the LA of the new location of the mobile terminal.

The new VLR determines the expected movement and searching costs for both options and the one that results in lower expected total cost is selected. If option 1 is selected, the searching cost for the first call after movement 1 is low because the HLR knows exactly the serving VLR of the mobile terminal. On the other hand, if option 2 is selected, the searching cost is higher because an intermediate VLR (the LA) is involved in locating the mobile terminal. After the arrival of the first call, the searching cost for subsequent calls are the same under both options. Our objective is therefore to minimize the expected movement cost and the searching cost for the first call after the movement. It is intuitive that if the call arrival rate is high and it is expensive to search for a mobile terminal, then it is more cost effective to register at the HLR right after a movement. Otherwise, it may be better off registering at the LA. We assume R_H to be the cost for registering the mobile terminal at the HLR (this includes the cost for deregistering the mobile terminal at its previous LA and VLR) and R_L to be the costs for registering the mobile terminal at the LA. We further assume that S_H to be the cost for searching the mobile terminal when the first call after the movement arrives if registration at the HLR was performed. Similarly, we assume S_L to be the cost for searching the mobile terminal if registration at the LA was performed. The expected cost for the movement and the first call after the movement if registration at the HLR was performed, denoted by E_H, is:

$$E_H = R_H + \rho S_H \tag{18}$$

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:

$$E_L = R_L + \rho S_L \tag{19}$$

where ρ is the probability that one or more call arrivals occur between movements. For Poisson call arrival and exponential RA residence time, ρ is given by Equation (16). For on-line application of dynamic local anchoring, the value of ρ can be estimated by one of the following methods:

- 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.

Location	Cost
A1	$2h_1$
A2	$2h_1$
A3	$2h_2$
A4	$2h_1 + 2h_2$
A5	$2h_1 + 2h_2$
A6	$2h_3$
A7	$2h_1 + 2h_3$
A8	$2h_1 + 2h_3$
A9	$2h_1 + 2h_3$

Table 5: Cost for reporting the location change to the HLR after a movement.

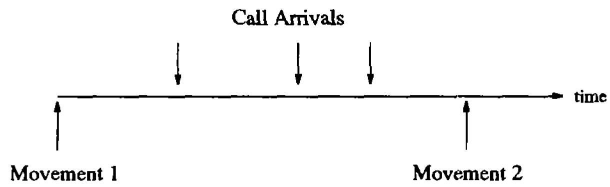

Figure 11: Call arrivals between two movements.

- 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.
- 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.

Depending on the current location type of the mobile terminal, the costs R_L and S_L can be obtained as given in Tables 3 and 1, respectively. The searching cost S_H is equal to s_1 (given in Table 1) since the serving VLR is the same as the LA. Based on the modified location registration procedure, the cost R_H for each location type is given in Table 5. The procedures for location registration and call delivery are given in Section 3. During step 2 of the modified location registration procedure, the new VLR of the mobile terminal determines the values of E_H and E_L according to Equations (18) and (19), respectively. If $E_H \leq E_L$, then the new VLR will report the location change to the HLR, otherwise it will report the location change to the LA. The location registration decision depends on the cost parameters and the location type of the mobile terminal. A performance model for DL must therefore be tailored based on the cost parameters.

For example, under one set of cost parameters, location change may have to be reported to the HLR if the mobile terminal moves to another LSTP region. However, when another set of cost parameters is used, it may not be necessary to report the location change to the HLR. We will conduct simulation experiments to determine the cost effectiveness of DL using the same assumptions as described in Section 4.2. Figure 12 gives the results of the experiments using the cost parameter sets given in Table 4. It is demonstrated in Figure 12(c) that the total cost of DL never exceeds that of the IS-41 scheme. As compared to the costs of SL scheme, the dynamic scheme obtains lower total cost for parameter sets 1, 4 and 6. The improvements to parameter sets 1 and 4 are due to limiting the use of local anchoring only when the expected costs can be lowered. 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. Figures 12(a) and (b) give 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. Searching cost is higher as in 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.

6 Conclusions

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 VLR and the HLR by messages between nearby VLRs. 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 VLR determines whether it should report the location change to the HLR or to the LA.

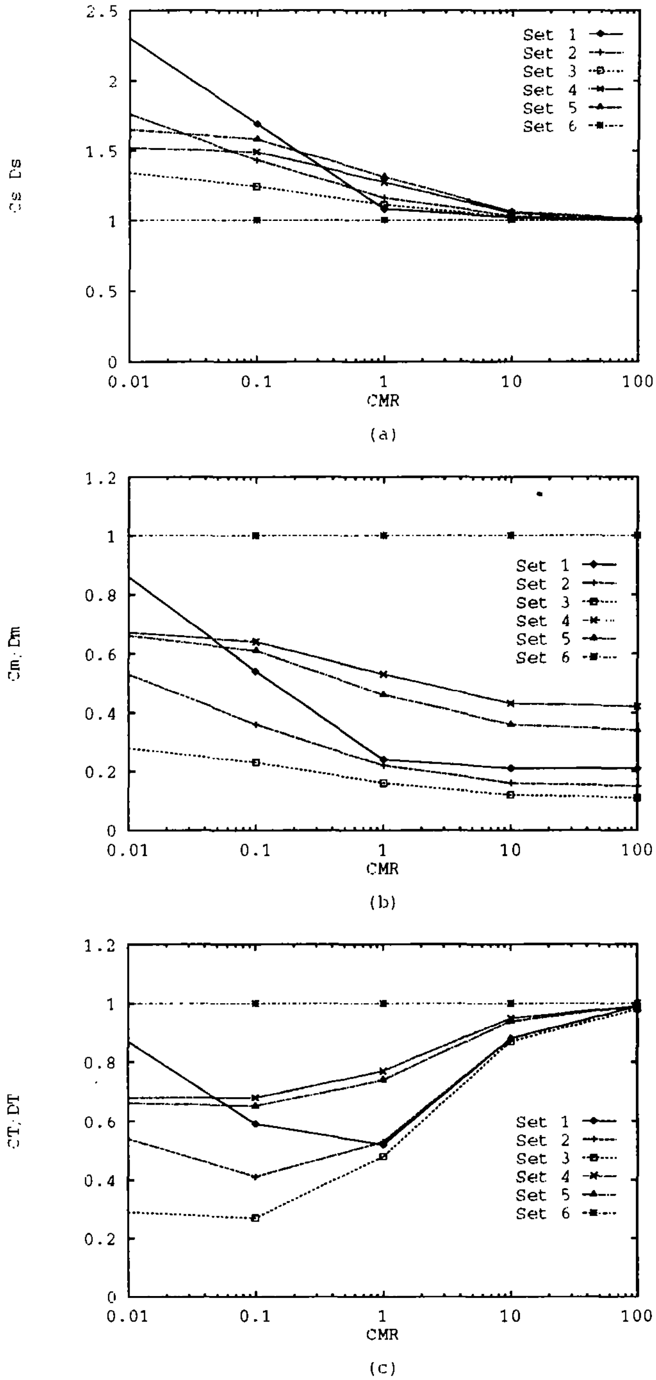

Figure 12: (a) Searching cost (b) Movement cost and (c) Total cost for the dynamic local anchoring scheme (DL).

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 the performance of the static scheme.

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. We are currently investigating several other local anchoring schemes.

References

[1] EIA/TIA, "Cellular Radio-Telecommunications Intersystem Operations," Technical Report IS-41 Revision B, EIA/TIA, 1991.

[2] R. Jain and Y.B. Lin, "An Auxiliary User Location Strategy Employing Forwarding Pointers to Reduce Network Impact of PCS," *to appear in ACM-Baltzer Journal of Wireless Network*, July 1995.

[3] R. Jain, Y.B. Lin and S. Mohan, "A Caching Strategy to Reduce Network Impacts of PCS," *IEEE Journal on Selected Areas in Communications*, Vol. 12, No. 8, October 1994.

[4] Y.B. Lin and R. Jain, "Mobility Management for Mobile Communications," submitted for publication.

[5] Y.B. Lin, "Determining the User Locations for Personal Communications Services Networks," *IEEE Transactions on Vehicular Technology*, Vol. 43, No. 3, pp. 466-473, August 1994.

[6] Y.B. Lin and S.K. DeVries, "PCS Network Signaling Using SS7," to appear in *IEEE Personal Communications*, June 1995.

[7] S. Mohan and R. Jain, "Two User Location Strategies for Personal Communications Services," *IEEE Personal Communications*, First Quarter 1994, pp. 42-50.

[8] M. Mouly and M.B. Pautet, "The GSM System for Mobile Communications," M.Mouly, 49 rue Louise Bruneau, Palaiseau, France, 1992.

Appendix

A Derivation of the Probability $q_i(n)$

We derive the probabilities that a mobile terminal's location belongs to **HOME**, **LOCAL** and **REMOTE**, respectively, n movements after the LA was 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 RAs along the x and the y directions such that:

$$x = x_i - x_j \tag{20}$$

$$y = y_i - y_j \tag{21}$$

where (x_i, y_i) and (x_j, y_j) are the coordinates for RAs i and j, respectively. For a two-dimensional PCN coverage area with square-shaped RAs as shown in Figure 9, a mobile terminal can move in four directions: LEFT, RIGHT, UP and DOWN. We assume r $(0 \leq r \leq n)$ 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:

$$l(r,x,y) = r + x \tag{22}$$

$$u(r,x,y) = \frac{1}{2}(n - 2r - x - y) \tag{23}$$

$$d(r,x,y) = \frac{1}{2}(n - 2r - x + y) \tag{24}$$

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

$$f(n,x,y) = \sum_{r=0}^{n} g(r,x,y) \tag{25}$$

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

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

$$g(r,x,y) = \frac{n!}{r!\,l(r,x,y)!\,u(r,x,y)!\,d(r,x,y)!} \tag{26}$$

otherwise, $g(r,x,y)$ is equal to 0.

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

$$\alpha_{i,j}(n) = \frac{f(n,x,y)}{4^n} \tag{27}$$

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 $q_1(n)$ 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 $q_1(n)$ is:

$$q_1(n) = \frac{f(n,0,0)}{4^n} \quad (28)$$

We assume that R is the set of all RAs in the anchor LSTP region. The expression for the probability $q_2(n)$ is:

$$q_2(n) = \frac{1}{d^2}\sum_{i\in R}\sum_{j\in R, j\neq i} \alpha_{i,j}(n) \quad (29)$$

The probability $q_3(n)$ is:

$$q_3(n) = 1 - q_1(n) - q_2(n) \quad (30)$$

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 RAs according to Figure 13. 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 size of each LSTP region be $d \times d$, the expressions for π_A and π_B are:

$$\pi_A = \frac{4(d-2)}{d^2} \quad (31)$$

$$\pi_B = \frac{4}{d^2} \quad (32)$$

Let $\gamma(n)$ 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 $\gamma(n)$ is:

$$\gamma(n) = \sum_{j\in N} \alpha_{i,j}(n) \quad (33)$$

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. Let R be the set of all RAs in the anchor LSTP region, the expression for $\beta_z(n)$ is given as:

$$\beta_z(n) = \frac{1}{d^2}\sum_{i\in R}\sum_{j\in z} \alpha_{i,j}(n) \quad (34)$$

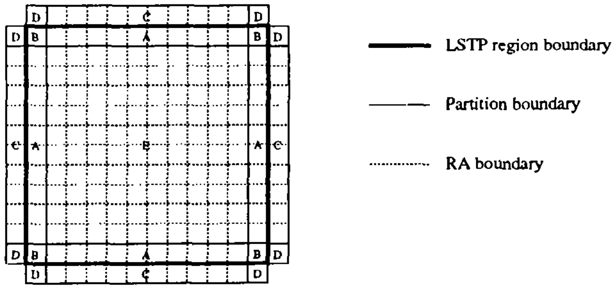

Figure 13: Partitions of an LSTP region.

We assume $\theta = 1 - \pi_A - \pi_B$, the probabilities $r_1(n)$ through $r_9(n)$ can be expressed in terms of θ, π_A, π_B, $\gamma(n)$ and $\beta_z(n)$ as:

$$r_1(n) = q_1(n-1)\left[\theta + \frac{3}{4}\pi_A + \frac{1}{2}\pi_B\right] \quad (35)$$

$$r_2(n) = q_1(n-1)\left[\frac{1}{4}\pi_A + \frac{1}{2}\pi_B\right] \quad (36)$$

$$r_3(n) = \frac{1}{16}\gamma(n-1)\left[4 - \pi_A - 2\pi_B\right] \quad (37)$$

$$r_4(n) = q_2(n-1)\left[\theta + \frac{3}{4}\pi_A + \frac{1}{2}\pi_B\right] - r_3(n) \quad (38)$$

$$r_5(n) = q_2(n-1)\left[\frac{1}{4}\pi_A + \frac{1}{2}\pi_B\right] \quad (39)$$

$$r_6(n) = \frac{1}{16}\pi_A\gamma(n-1) + \frac{1}{8}\pi_B\gamma(n-1) \quad (40)$$

$$r_7(n) = \frac{1}{4}\left[\beta_C(n-1) + \beta_D(n-1)\right] - r_6(n) \quad (41)$$

$$r_8(n) = \frac{3}{4}\left[\pi_A - \beta_A(n-1)\right] + \frac{1}{2}\left[\pi_B - \beta_B(n-1)\right] + \left[\theta - \beta_E(n-1)\right] \quad (42)$$

$$r_9(n) = \frac{1}{4}\left[\pi_A - \beta_A(n-1) - \beta_C(n-1)\right] + \frac{1}{2}\left[\pi_B - \beta_B(n-1) - \beta_D(n-1)\right] + \frac{1}{4}\beta_D(n-1) \quad (43)$$

where $q_1(n)$ and $q_2(n)$ are given in Appendix A.