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Reducing Call-Setup Time for Location Tracking with Distributed HLR and Pointer Forwarding*

Kuen-Liang Sue, Chien-Chao Tseng, and Yi-Sho Lai

Department of Computer Science and Information Engineering
National Chiao-Tung University
Hsinchu, Taiwan 300, R.O.C.
klsue,cctseng,yslia@csie.nctu.edu.tw

Abstract

One of the main challenges in PCS is to locate many mobiles that may move frequently from place to place. This location tracking operation involves many network signals flow and database queries. In addition to the two-level hierarchical strategy in IS-41 and GSM, several strategies have been proposed to improve the efficiency of location tracking. Pointer forwarding was used to reduce the expensive HLR accesses. Previously , distributed HLRs scheme was proposed to prevent HLR becoming a bottleneck in the signaling network. However, the length of a forwarding pointer chain may be lengthened in a distributed HLR environment. In this paper, we propose a more efficient strategy to overcome this potential problem. This strategy attemps to migrate the locating chains in a distributed HLR system when a mobile issues a registration operation. As a consequence, the length of any forwarding pointer chain does not exceed one in our strategy. Simulation results indicate that our strategy significantly decreases the locating cost. In fact, this strategy provides an upper bound of location tracking time owing to the fact that its length of any locating path does not exceed one. Furthermore, obsolete entries in local databases (VLRs) can be reclaimed in this strategy.

1 Overview

The personal communication service, henceforth called PCS, is a system that aims to allow for communication anywhere in the world. Such a system attemps to locate many mobiles that may move frequently from place to place [1]. Location tracking operation in a PCS network is expensive because that many signal flow and database queries are needed to achieve such a task. Moreover, locating a mobile is also a time-consuming process. In fact, the time to deliver an incoming call to a mobile is dominated by the locating time. If a location tracking strategy is efficient, call delivery time is shortened significantly. Therefore, devising a good location tracking strategy is necessary in PCS system.

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Common location tracking strategies use two-level hierarchical mechanism to maintain two classes of databases of user location information [2]. One class of the databases is called Home Location Register (HLR), and the other Visitor Location Register (VLR).

In addition to a two-level hierarchical strategy in IS-41 and GSM [2], several methods have been proposed to improve the efficiency of location tracking [3, 4, 5, 6, 7, 8, 10]. The pointer forwarding strategy has been proposed to avoid the expensive HLR access each time a mobile moves to a new Registration Area (RA) [7]. Lin suggested that distributing HLRs in several areas can prevent HLR from becoming a signal bottleneck in the signaling network [8]. In that study, the forwarding pointer strategy and the concept of distributed HLRs are combined to provide a new locating tracking strategy. It uses the characteristic of forwarding pointers to make the concept of distributed HLR [3] more attractive and efficient. However, a potential limitation of the strategy is that the length of forwarding pointer chains may become too long. Therefore, this paper provides a more efficient strategy to overcome such a limitation and makes the notion of distributed HLRs more feasible.

2 Related location tracking strategies

2.1 Location tracking in IS-41

In IS-41 protocol, all service areas are divided into many registration areas (RA) [12]. To record every mobile's location information, there are two kinds of databases, HLR/VLR. When a user subscribes to the service, a record associated with this user is created in the system database, HLR. As a mobile roams and arrives to a new RA, a record for this mobile is created in this RA's database, i.e., VLR. In fact, some RAs may share a VLR. To simplify research, we assume that every RA has its own VLR. Notably, Mobile Switching Center (MSC) is near by the associated VLR [2]. "VLR" is used to represent "MSC/VLR" in the later content. Signaling flow between MSC and VLR will be ignored in this article.

In IS-41, if a mobile moves from some RA to another one, it must be registered at the VLR of the new RA by sending a registration-request message [2].

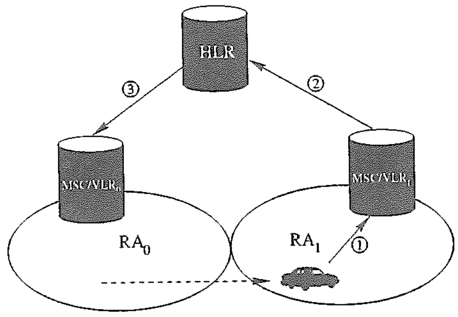

Figure 1: Registration in IS-41

This VLR creates a temporary record for the mobile and sends a message to inform the HLR about the mobile's new location. To erase the obsolete record in the VLR of the old RA, HLR sends a registration-cancel message to the old VLR [2, 9, 11]. The composition of the above actions is referred to as *registration* operation and is shown in Figure 1.

When the PCS system attempts to deliver a call to a mobile, another procedure called *call delivery* is required. Location tracking is the primary task in this procedure as described below. [2, 13]

1. When an incoming call occurs, a table lookup technique called Global Title Translation (GTT) is required at Signal Transfer Pointer (STP) to identify the address of the HLR serving the called mobile m.
2. A *location-request* message is sent to query the HLR of the mobile m.
3. The HLR determines the VLR currently serving m and queries it by sending *route-request* signal.
4. The VLR forwards the query message to the Mobile Switching Center (MSC). If the mobile m can receive the call, the MSC returns a routable address called Temporary Local Directory Number (TLDN) to the VLR.
5. The VLR forwards the TLDN back to the originating MSC via the HLR of the mobile m.
6. When the originating MSC receives the TLDN, it routes the call to the MSC where the mobile m is located.

By cooperating with these two procedures, the system can locate a mobile and deliver a call to it correctly. [2]

2.2 Pointer forwarding with single HLR scheme

For a mobile which frequently moves across RAs but seldom has an incoming call, traditional IS-41 registration operation is wasted in the network cost. In traditional IS-41, every registration operation must update HLR to record the most recent location of a

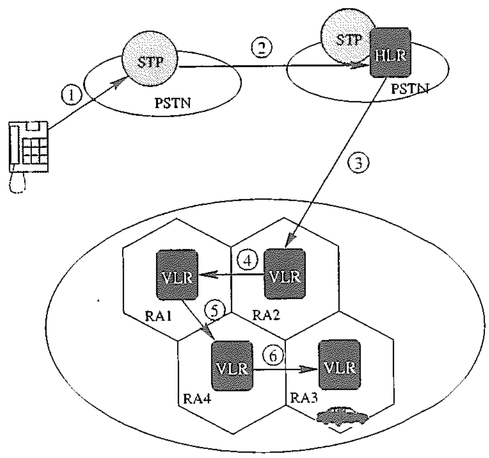

Figure 2: Location tracking in PFSHLR

mobile. However, never receiving any call, the mobile may leave to another RA again and initiate another registration operation in the new RA. In fact, access to HLR is much more expensive than access to VLR. Based on these observations, pointer forwarding scheme is proposed to reduce the waste.

In a pointer forwarding scheme, registration operation is changed slightly [6, 7]. A mobile coming to a new RA sends a registration message to the VLR of the new RA. Instead of sending a message to inform HLR, the new VLR sends a message to inform the old VLR about the mobile's leaving. On receiving this message, the old VLR deletes the obsolete record for the mobile and creates a forwarding pointer pointing to the new RA [6]. Figure 2 depicts the state transition and also shows the process to locating a mobile.

2.3 The pointer forwarding with distributed HLRs scheme

In IS-41, distributed HLRs require multiple HLR updates when a mobile registers at a new RA. Lin proposed a pointer forwarding with distributed HLRs (PFDHLR) scheme to eliminate this overhead in a distributed HLR environment [8].

In this scheme, HLRs are distributed in remote Public Switching Telephone Networks (PSTN). PFDHLR assumes that a distributed HLR is near by the STP that performs GTT. Like Pointer Forwarding with Single HLR (PFSHLR) strategy, every HLR in PFDHLR records an RA where a mobile may exist. In fact, the RA is the position where the mobile is found the last time by individual HLR. Different distributed HLRs may imply different RAs. All registration processes are the same as in PFSHLR.

When an incoming call is originated from some remote PSTN, the HLR will be directly queried. This fact suggests that GTT is not required because the distributed HLR is near by STP. Next, the HLR at that PSTN queries the VLR recorded in the entry associated with the callee. If the mobile is found in this RA, a call will be delivered to it. Otherwise, the

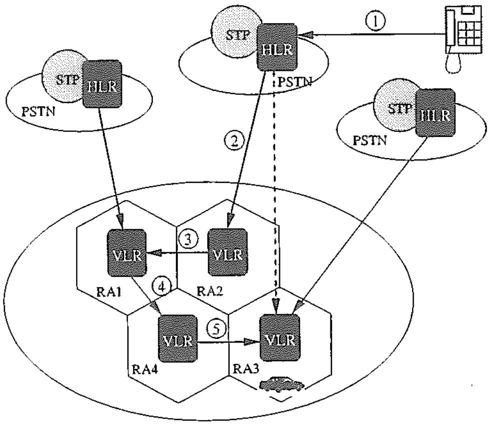

Figure 3: Location Tracking in PFDHLR

system will trace the mobile through the forwarding pointer chain starting from that RA. Figure 3 depicts this call delivery process. After completing the locating operation, the HLR will change the record for the called mobile to point to the RA where the mobile is found, as Figure 3 indicates by dotted line.

This scheme effectively and efficiently implements the distributed HLR notion. However, it has some potential side effects. The length of pointer chain may be lengthened. Because of distributing HLRs in several regions, the total incoming calls will be shared by all HLRs. Therefore, the average call arrival rate in each distributed HLR is 1/N times of that in PFSHLR. Call arrival rate divided by the frequency of crossing RA boundary is named call-to-mobility ratio. Restated, the call-to-mobility ratio for each distributed HLR is 1/N times of that is PFSHLR. According to the simulation of [8], the expected length of each pointer chain increases considerably when the call-to-mobility ratio is small.

3 Location tracking with one_step pointer forwarding and distributed HLR

To overcome the potential problem in PFDHLR, we propose a new location tracking strategy with one-step pointer forwarding and distributed HLRs.

3.1 Overview of our strategy

Similar to PFDHLR, our strategy also incorporates the concept of distributed HLRs with a pointer forwarding. Every distributed HLR has one record for an authorized mobile. This record records the individual RA/VLR where a mobile is found the last time by an individual HLR. Different HLRs may record different RA/VLR as the head of their own locating paths, so they may have different locating paths; therefore, one cellular system with N distributed HLRs may have n different locating pointer chains, $n \leq N$, for the same mobile. Whenever a mobile registers at a new RA, the VLR in the new RA will maintain an entry for this mobile. This entry is the common rear of the n locating pointer chains. Similar to a double link list, every such entry must record the previous nodes in the n locating pointer chains. In this manner, VLR can send de-registration message through all locating paths. This message is forwarded to proper VLRs via the previous link in each entry. Next, all locating paths are migrated to guarantee that each pointer chain's length among VLRs does not exceed one. This property is always true regardless of which HLR an incoming call originates from. Based on this characteristic, we call it "One-Step Pointer Forwarding Strategy for Location Tracking in Distributed HLR Environment".

Prev.			TAG			Mobile_ID	Next
0	1	2	0	1	2		
P	P	P	B	B	B	Integer	P

P : Pointer B : Bit

Figure 4: Data structure of each entry in VLR

3.2 Data structure definition and assumption

Before describing how our strategy works, the related data structure must be defined. For simplicity, we assume that there are three distributed HLRs in a cellular system. Figure 4 represents the structure of an entry. The four fields are explained individually as follows.

1. Prev: It's a pointer array.
   "Prev" is an abbreviation for "Previous." In this example, there are three elements in this array. Each element is the address of a previous VLR in some locating pointer chain. This system may have three locating chains existing at the same time since there are three distributed HLRs in the system and each HLR has its own searching path. Thus, a VLR can appear in three paths at most.

2. TAG : It's a 3-bit flag.
   Each bit corresponds to one distributed HLR. If any HLR_i records that the mobile associated with this entry is in this VLR now, TAG_i will be set to 1. Otherwise, TAG_i is always 0. This flag will be used to determine whether this entry will be reclaimed or not.

3. Mobile ID : This field records the ID of the mobile associated with this entry.

4. Next : It's a forwarding pointer which points to the next VLR in some locating chains.

3.3 One-step pointer forwarding strategy

In this subsection, we describe our strategy in terms of three system events: Handset Initiation, Registration, and Call Delivery.

3.3.1 Handset initiation

When a mobile m_0 is initialized in some RA, it will send a INIT(m_0) signal to the VLR of this RA. As the VLR receives INIT(m_0), it must perform the following two actions.

* Create an entry for the mobile m_0.
* Inform all distributed HLRs of this Initiation.

By the above actions, all the records for m_0 in all distributed HLRs will point to this VLR.Therefore all distributed HLRs know where to deliver calls to this mobile now. This VLR has become the head node in all the forwarding pointer chains for m_0.

3.3.2 Registration

When a mobile m_0 moves across the boundary of an RA, e.g. from RA_0 to RA_1, it will send a REGISTRATION(m_0, V_0) signal to the VLR of the new RA. When the VLR receives the REGISTRATION signal, the following actions must be performed:

* Inform the old VLR of the mobile's leaving by sending a DEREGISTRATION signal.
* Create/Modify the entry for this mobile.

Sending a DEREGISTRATION to the old VLR will initiate proper modification in all searching paths to maintain the length of all locating paths not more than one.

On receiving the DEREGISTRATION signal, the old VLR reacts as follows:

* Forward the DEREGISTRATION signal to each VLR in the pointer array Prev.

  In some case [16], the new VLR originating the DEREGISTRATION signal may exist in the Prev array. To avoid unnecessary signal traffic, the old VLR will not forward the DEREGISTRATION signal to the new VLR.

* If all TAG values of the designated entry are 0, the VLR reclaims the entry.

  m_0 has left and no locating path for m_0 goes via this VLR, so the entry for m_0 can be reclaimed.

* If any TAG value is not 0:

  1. Set the pointer Next to point to the VLR originating the DEREGISTRATION signal.
  2. Clear the pointer array Prev.
  3. Send ACK signal to the VLR from which this DEREGISTRATION signal originated.

  This case implies that this VLR is still in some locating path and this entry can not be reclaimed. Therefore, we set Next to point to the current position where m_0 locates now.

  On receiving the forwarded DEREGISTRATION signal, a VLR will perform the same actions as described above.

When the new VLR receives signal ACK, it must do one thing:

* Add the RA which originates this ACK to the previous array.

3.3.3 Call delivery

If a HLR H_0 wants to deliver a call to a mobile m_0, it will send a Call_Setup_Req(m_0, H_0) signal to the VLR pointed to by the entry associated with m_0 in H_0. When the VLR receives this signal, it determines whether the mobile m_0 has left or not.

If m_0 has left, the VLR will perform the following two actions.

* Forward the Call_Setup_Req(m_0,H_0) signal to the VLR pointed to by Next pointer.
* Reset TAG_0 and reclaim this entry if all TAGs are 0.

If m_0 still exists, the VLR will return the call setup result to H_0, and set TAG_0 to 1. On receiving the call setup result, H_0 will change the record associated with m_0 to point to the VLR. The call setup result will be a TLDN if m_0 can receive call now; otherwise, the call setup result will be a failure message.

3.3.4 The detailed protocol

We have programmed this protocol to check its validity. All the detailed protocol and detailed validity analysis can be found in [16]. According to those results, this protocol always works well as expected. It guarantees that not more than one forwarding pointer will be traced to locate a mobile regardless of which remote PSTN an incoming call originates from.

4 The performance analysis model

This section introduces the analytical model of OSPFDHLR, PFDHLR and PFSHLR for call delivery network cost in detail. For fairness and convenience, we follow the performance analysis model in [8] which has made a comparison between PFDHLR and PFSHLR in terms of network cost.

4.1 Assumptions

For both PFDHLR and OSPFDHLR, HLRs are distributed in remote PSTNs. A reasonable assumption is that each distributed HLR is near by the STP.

In addition, some network cost estimates are made as follows to simplify the comparison.

1. The message passing cost from the caller to the GTT STP in PFSHLR is normalized to 1;
2. In both OSPFDHLR and PFDHLR, message passing cost from the caller to the distributed HLR is 1;
3. The message passing cost from the GTT STP to the HLR in PFSHLR is 1;
4. The query cost from a HLR to a VLR in all three strategies is 1; and

5. The pointer traversing cost from one VLR to another is δ.

According to above assumptions, the analytical model can estimate the required network cost for locating a mobile in three strategies. The next subsection explains this model in detail.

4.2 The analytical model

One common and important term in these three strategies is how long the pointer chain will be. This important term is referred as $E[k]$,i.e. the expected number of forwarding pointers in locating chain. $E[k]$ can be derived from the following equation

$$E[k] = \sum_{K=0}^{\infty} E[k|K]\alpha(K) \tag{1}$$

In the real world, a mobile may move across RA boundary K times between two consecutive incoming calls and the number of resulting forwarding pointers is k. It should be understood that k is not always equal to K. The exact equation is K≥k. The equal mark is true only when a mobile never revisits any RA between two consecutive incoming calls.

$\alpha(K)$ is the probability that a mobile moves cross RA boundary K times between two consecutive incoming calls. From the appendix in [8], $\alpha(K)$ can be calculated as follows

$$\alpha(K) = \begin{cases} 1 - \dfrac{1 - f_m^*(\lambda_c)}{\theta} & K = 0 \\ \dfrac{1}{\theta}[1 - f_m^*(\lambda_c)]^2[f_m^*(\lambda_c)]^{K-1} & K > 0 \end{cases} \tag{2}$$

where λ_c is the call arrival rate and λ_m is the frequency of crossing RA boundary, $\theta = \frac{\lambda_c}{\lambda_m}$ is the call-to-mobility ratio, and f_m^* is the Laplace-transform of the mobile residential time in a RA [8, 14, 15].

In this model, the residential time is assumed to have a Gamma distribution. This assumption has two reasons. One is that Gamma distribution can has the desirable property to fit an arbitrary distribution by setting appropriate parameters. Another reason is that the Gamma distribution has a simple Laplace transform which is as follows.

$$f_m^*(s) = \left(\frac{\lambda_m\gamma}{s + \lambda_m\gamma}\right)^{\gamma} \text{ where } \gamma = \frac{1}{V\lambda_m^2} \tag{3}$$

By using Equation (2)(3), different λ_c, λ_m, V, and K can be set to obtained the corresponding probability $\alpha(K)$.

To derive $E[k]$, another critical factor is E[k|K] which means the expected length of locating pointer chain for a given K. E[k|K] can be computed by a simulation technique called two-dimensional random walk. In a two-dimensional random walk, a mobile may move in one of four possible direction with equal probability 0.25. However, in the real world, mobile's moving pattern usually exhibits spatial locality. That is, a mobile tends to roam within a bounded area. To simulate this characteristic, a two-dimensional random walk within a bounded region is used to model a mobile's moving pattern. Figure 5 illustrates a bounded area with size 16.

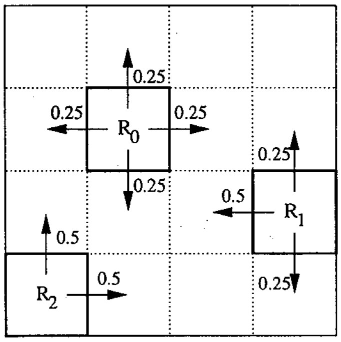

Figure 5: Two-dimensional random walk within bounded area

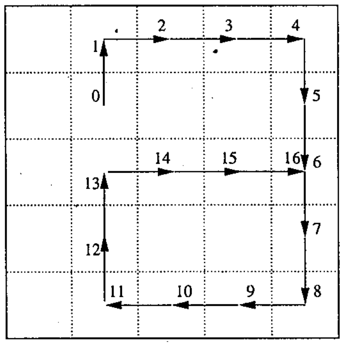

Figure 6: an example for K=16 and k=6

For a given K, we can determine K consecutive movement directions with the probability introduced above and compute the resulting length of locating pointer chain k. An example is shown in Figure 6, K=16 and k=6. This experiment is repeated with the described probability until the E[k|K] values are convergent. By such simulation, E[k|K] can be computed for any given K. Now, the expected length of the locating pointer chain, i.e. $E[k]$, can be computed from Equation(1).

Because the value of $\alpha(K)$ is significantly affected by θ, $E[k]$ is a function of θ. To express this fact, $E[k]$ is re-expressed as E[k| θ]. According to [8], the locating cost in PFSHLR for a call delivery is

$$C_S = 3\left(\frac{N-1}{N}\right) + 2\left(\frac{1}{N}\right) + E[k|\theta]\delta \tag{4}$$

where N is the number of distributed HLRs at remote PSTNs. Based on the assumption that incoming calls are uniformly distributed among N remote PSTNS, locating cost for a call delivery in PFDHLR is

$$C_D = 2 + E[k|\frac{\theta}{N}]\delta \tag{5}$$

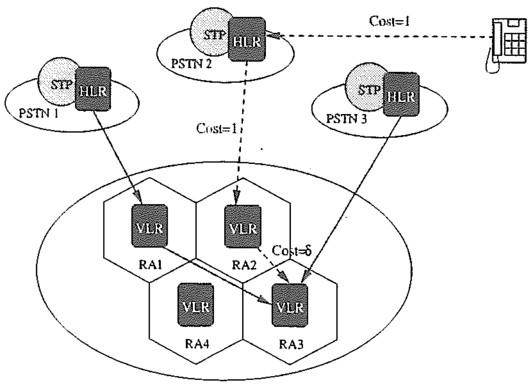

Figure 7: The process of locating a mobile for call delivery from remote PSTN in OSPFDHLR

As mentioned in Section 3, OSPFDHLR guarantees that the length of forwarding pointer chain does not exceed one. When an incoming call arrives, the locating path is traced as Figure 7. Therefore, for OSPFDHLR, the cost of locating a mobile for a call delivery is

$$C_O = \begin{cases} 2+\delta & E[k|\frac{\theta}{N}] \geq 1 \\ 2+E[k|\frac{\theta}{N}]\delta & E[k|\frac{\theta}{N}] < 1 \end{cases} \quad (6)$$

By using Equations(4)(5)(6), simulations are performed for these three strategies.

4.3 Simulation results

Five factors influence the simulation results. They are described as follows:

N: The amount of distributed HLRs in system.

S: The size of the bounded square region in which the mobile is restricted due to spatial locality.

V: The variance of the resident time distribution in this simulation.

δ: The cost for traversing a forwarding pointer from a VLR to another.

θ: Call-to-mobility ratio, $\theta = \frac{\lambda_c}{\lambda_m}$ where λ_c is the call arriving rate and λ_m is the frequency of crossing a RA boundary.

Figures 8~11 present the costs for PFSHLR, PFDHLR, and OSPFDHLR with different parameters mentioned above. To more thoroughly examine the tendency how the spatial locality affects the performance of three strategies, Figures 12 and 13 provide further exploration.

4.4 Numerical analysis

4.4.1 General analysis

Figure 8 summarizes the simulation results for per-pointer traversing cost with δ=0.5. The other parameters are the size of the locality restricted area S=16, the amount of distributed HLRs N=2, and the variance of resident time distribution V=1.0. As shown in Figure 8, PFDHLR outperforms PFSHLR in such a condition. Another tendency worth noting is that the costs for PFDHLR and PFSHLR raise quickly when θ is decreasing from 0.4. Figure 9 considers high per-pointer traversing cost, e.g. δ=1.0. Figure 8 indicates that 14.56% improvement are made from OSPFDHLR over PFDHLR for δ=0.5. For δ=1.0, 22.59% improvement can be expected as Figure 9 indicates.

Figure 10 consider the case of residential time with high variance. In this figure, V=10.0 and other parameters are the same as in Figure 9. Comparing Figures 9 and 10 reveals that the curves are rather similar. The costs in Figure 10 are a little smaller than that in Figure 9. The reason for this phenomenon is that $E[k]$ will be shortened slightly when variance is increased. This property has been explained in [8]. In Figure 10, the improvement made from OSPFDHLR over PFDHLR are 16.20%.

Figure 11 consider more distributed HLRs, e.g. N=4, in system. Comparing Figure 11 and 8, PFDHLR still outperforms PFSHLR but is very close to PFSHLR as $\theta \leq 0.4$. The reason is that the call arrival rate is divided by 4 now due to the assumption that the incoming calls are uniformly shared by distributed HLRs. This division makes θ decrease and the expected number of forwarding pointers increase significantly. Under such a condition, the improvement made by OSPFDHLR becomes 19.84%. More completely numerical analysis is provided in [16].

4.4.2 Further exploration into spatial locality

Figures 12 and 13 demonstrate how the spatial locality has influence on these three strategies. Figure 12 plots the average costs of the three strategies for different S values. The values of other parameters are 0.1≤ θ ≤6.4, N=4, V=1.0, and δ=0.5, as shown in this figure. Figure 13 considers four distributed HLRs (i.e. N=4) in the system. Figure 12 indicates that PFDHLR always outperforms PFSHLR as δ=0.5. The average costs for PFSHLR and PFDHLR all raise slightly and the curve tends to become a horizontal line with increasing S. Furthermore, if the number of distributed HLRs, N, increases from 2 to 4, PFSHLR may outperform PFDHLR for δ = 0.5 and S>36 as shown in Figure 13.

This comparison between PFDHLR and PFSHLR provides a manner of determining which locating strategy is appropriate for subscribers with different spatial locality. For example, PFDHLR should be more preferred than PFSHLR under the condition in Figure 13 when $S < 36$. However, a more ideal choice is OSPFDHLR. As those figures demonstrate, OSPFDHLR always outperforms the other two strategies in terms of performance analysis.

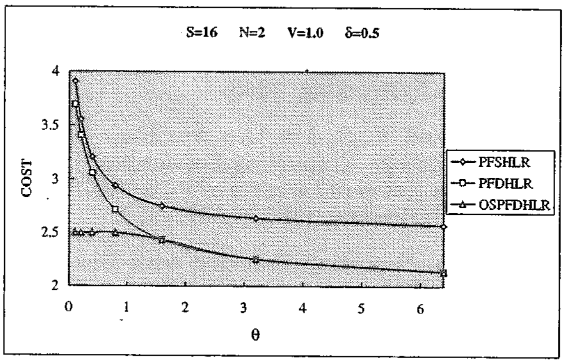

Figure 8: The locating costs of three strategies with S=16, N=2, V=1.0, $\delta = 0.5$.

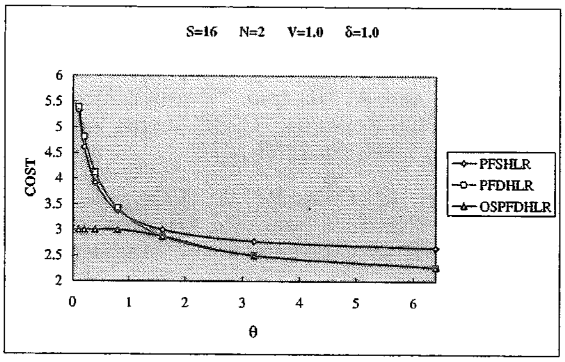

Figure 9: The locating costs of three strategies with S=16, N=2, V=1.0, $\delta = 1.0$.

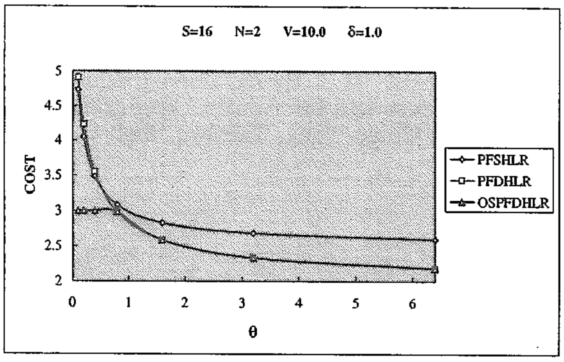

Figure 10: The locating costs of three strategies with S=16, N=2, V=10.0, $\delta = 1.0$.

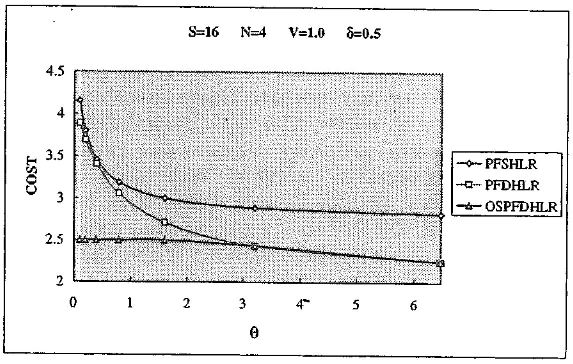

Figure 11: The locating costs of three strategies with S=16, N=4, V=1.0, $\delta = 0.5$.

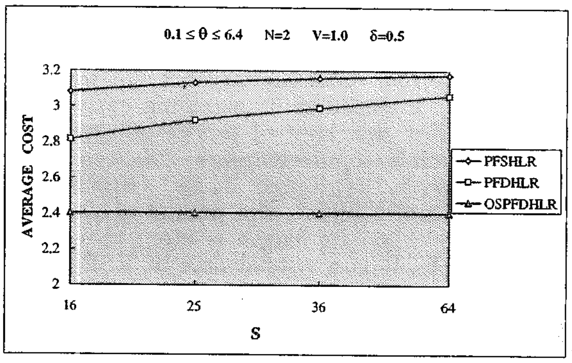

Figure 12: The average costs for different spatial locality.(N=2, V=1.0,$\delta = 0.5$.)

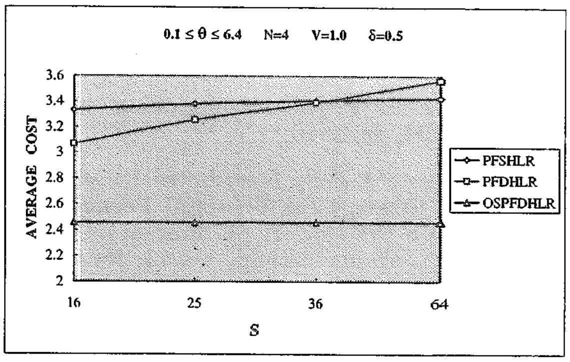

Figure 13: The average costs for different spatial locality.(N=4, V=1.0,$\delta = 0.5$.)

5 Conclusion

In this paper, an efficient *location tracking strategy*, namely One-Step Pointer Forwarding with Distributed HLRs, is proposed. It can properly adjust the forwarding pointers in VLRs and guarantees that the length of any pointer chain does not exceed one, regardless of where the distributed HLR a call originats. It only properly adjusts the pointers between VLRs instead of using an expensive HLR access. Simulation results demonstrate that compared with PFDHLR, OSPFDHLR can reduce call delivery time/cost significantly, particularly when the number of distributed HLRs is growiing.

In fact, OSPFDHLR provides an upper bound of the location tracking time. The reason is that the locating pointer chain does not exceed one in any case. This merit is useful in providing high quality of service in a distributed HLRs system. Another salient feature of OSPFDHLR is the ability to reclaim the invalid entry in VLRs.We believe that the major contribution of this article is to strengthen the feasibility and attractiveness of the concept of distrubuted HLRs.

One potential problem in OSPFDHLR is that adjusting the forwarding pointers needs some extra signaling capacity between VLRs. For a mobile which often moves across RA boundary but not frequently receives calls, a considerable signaling capacity will be wasted. For this kind of service subscriber, we suggest a flexible countermeasure, "K-Step Pointer Forwarding with Distributed HLRs" (KSPFDHLR) strategy. In KSPFDHLR, the pointer chain will be adjusted only when its length is more than K. In fact, OSPFDHLR is a special case of KSPFDHLR, $K=1$. We think that how to find a proper K to suit subscribers with certain mobility pattern is a worthwhile research topic in the future.

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